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Nozzle Angle Optimization for Enhanced Flow Behavior and Efficiency in Rocket Propulsion By Amrish Sekar

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Abstract

The increasing demand for reliable and efficient propulsion systems in the new generation of rockets highlights the importance of optimizing nozzle design. Among the critical parameters influencing performance, nozzle geometry, and in particular the exit angle, plays a fundamental role in determining the behavior of exhaust gases under varying atmospheric conditions. This paper investigates how variations in nozzle angle influence flow separation, shock wave formation, and exhaust expansion at different altitudes. Using computational fluid dynamics (CFD) simulations, the study examines the effects of nozzle exit pressure ratios on flow stability and thrust efficiency across a range of simulated altitude conditions. Results indicate that nozzle angle significantly affects the onset of flow separation and shock interactions within the nozzle, which in turn impacts overall performance. These findings underscore the need for tailored nozzle designs optimized for multi-stage rocket applications, where performance must remain efficient across changing atmospheric pressures.

I. Introduction

Nozzle geometry plays a critical role in rocket propulsion, as its design directly impacts thrust generation, shock formation, and overall flow behavior, making its optimization essential for efficient performance across varying altitudes. Nozzle geometry is a key factor in rocket propulsion, affecting thrust, pressure distribution, and flow behavior. The **de Laval nozzle**, with its converging-diverging design, accelerates subsonic flow to supersonic velocities, making parameters like throat size and expansion ratio critical for efficiency [1][2]. Optimal performance occurs when exit pressure matches ambient pressure, but this rarely happens during ascent due to rapidly changing atmospheric conditions, leading to over- or under-expansion [3][4]. Recent studies using CFD and the method of characteristics show that nozzle contour design strongly influences shock formation, Mach distribution and overall thrust [5][6].

Modern nozzle designs aim to balance efficiency and adaptability across altitudes by optimizing parameters like the expansion ratio and diverging angle. Phenomena such as shock diamonds, expansion fans, and flow separation arise when nozzle geometry is not matched to ambient conditions. Research by Rao et al established fundamental contouring techniques for bell nozzles, which remain the basis for current optimisation approaches [7]. Recent CFD studies have further examined altitude-compensating nozzle designs, demonstrating how geometry variations can mitigate efficiency losses due to over-expansion or under-expansion [8][9].

Additional research by Hagemann et al and Nasuti et al highlights the importance of accurate shock prediction and flow separation analysis in performance optimization.

Altitude-compensating concepts like aerospikes and plug nozzles have also been analysed for their adaptability, although their complexity often limits practical application[9][10][11][12].

This study builds on such work by analysing how small changes in nozzle half-angles affect flow stability, shock formation, and thrust, using a computational approach that combines classical gas dynamics with modern CFD tools.

II. Literature Review

Previous research on nozzle performance, from classical isentropic flow theory to modern CFD studies, highlights how geometry, contouring, and advanced designs influence thrust, shock behavior, and flow separation, yet small-angle variations remain insufficiently explored.

Classical isentropic flow theory provides the basis for nozzle performance predictions, with works like Anderson's *Modern Compressible Flow* and Sutton & Biblarz's *Rocket Propulsion Elements* establishing the relationships between nozzle geometry, Mach number, and thrust. Rao's contour designs demonstrated how bell nozzles can achieve near-optimal expansion across a range of conditions, minimising shock losses[7][13][14].

More recent studies have incorporated CFD and optimisation techniques. For example, Yadav et al. demonstrated that diverging angles below 35° minimize flow separation at sea-level conditions [15]. At the same time, other research has explored altitude-compensating designs like the dual-bell and plug nozzle configurations [8]. Similarly, research done by Hagemann et al suggests the same results[10]. Onofri et al showed that nozzle geometry affects separation behaviour and side-load phenomena, which are critical in launch vehicle applications[9].

Further studies by Stark et al. and Ivanco emphasise the importance of real-gas effects and viscous dissipation, particularly when using advanced propellants[16][17]. Investigations by Gao et al on 3D nozzle optimization have also demonstrated that nozzle wall curvature and length interact with angle variations to influence performance[18].

Despite these advances, a detailed comparative analysis of small-angle variations (e.g., $\pm 1\text{-}2^\circ$) on flow stability and thrust remains underexplored. This study addresses that gap using a CFD-based parametric analysis.

III. Numerical Model and Computational Methodology

A. Geometry and Design Parameters

The de Laval nozzle designs considered in this study were defined by:

Parameter	Values / Description
Converging half-angles	$13^\circ - 18^\circ$
Diverging half-angles	$28^\circ - 32^\circ$

Throat diameter	Fixed for all cases
Expansion ratio	3.365 (exit-to-throat area ratio)
Nozzle length	Adjusted to maintain consistent expansion ratios

Table 1.1.

These parameters were selected based on recommendations for minimising shock losses and maintaining boundary layer stability [16][15][17]. The geometry design followed standard practices outlined by Huzel et al and Sutton et al [19][14].

B.Flow Conditions and Initial Property Estimation

To obtain specific values for the initial thermodynamic and gas properties, NASA's Chemical Equilibrium with Applications (CEA) program was used. The chamber pressure, oxidiser-to-fuel ratio, chamber temperature, and pressure ratio were input into the program, and NASA CEA generated realistic outputs for properties such as chamber density, molecular weight, specific heat capacity, and specific heat ratio. These parameters were then used as inputs for both the CFD simulation setup and the derivation of nozzle design equations.

Parameter	Value	Unit
Thrust	3.5	kN
Chamber Pressure, p_0	20	bar
Chamber Temperature, T_0	2430.6	K
Chamber Density, ρ_0	2.0714	kg/m ³
Exit Pressure	1.01325	bar
Mass Flow Rate	1.72	kg/s
Specific Heat Ratio	1.2525	-
Molecular Weight	20.93	kg/k-mol
Specific Gas Constant	397.23	J/kg-K
Specific Heat	2016.7	J/kg-K
Oxidizer-Fuel Ratio	2.75	-
Pressure Ratio	19.74	-
Convergent Half-Angle	30	degrees
Divergent Half-Angle	15	degrees

Table 1.2. Design Constraints (Initial Properties from NASA CEA)

C. Nozzle Parameter Derivation

Nozzle throat and exit properties were determined using classical area-Mach and isentropic flow relations [13][14]. The main equations are:

Chamber Density:

$$\rho_c = \rho_t \left(1 + \frac{\gamma - 1}{2} M_e^2 \right)^{\frac{1}{\gamma - 1}}$$

Chamber Temperature:

$$T_c = T_t \left(1 + \frac{\gamma - 1}{2} M_e^2 \right)$$

Throat Velocity:

$$V_t = a_t = \sqrt{R \cdot \gamma \cdot T_t}$$

Throat Area:

$$A_t = \frac{\dot{m}}{\rho_t \cdot V_t}$$

Pressure Ratio:

$$\frac{P_e}{P_c} = \left(1 + \frac{\gamma - 1}{2} M_e^2 \right)^{-\frac{\gamma}{\gamma - 1}}$$

Temperature Ratio:

$$\frac{T_e}{T_c} = \left(1 + \frac{\gamma - 1}{2} M_e^2 \right)^{-1}$$

Exit Speed of Sound:

$$a_e = \sqrt{R \cdot \gamma \cdot T_e}$$

Exit Velocity:

$$V_e = M_e \cdot a_e$$

Area Ratio:

$$\frac{A_e}{A_t} = \frac{1}{M_e} \left[\frac{2}{\gamma + 1} \left(1 + \frac{\gamma - 1}{2} M_e^2 \right) \right]^{\frac{\gamma + 1}{2(\gamma - 1)}}$$

Table 1.3.

The computed geometric values are listed below:

Parameter	Value	Unit
Throat Area	0.0012846	m ²
Exit Mach	2.56	-
Exit Temperature	1332.24	K
Exit Velocity	2045.12	m/s
Exit Area	0.0043225	m ²
Area Ratio	3.365	-
Throat Radius	0.020221	m
Exit Radius	0.037093	m
Throat Curvature Radius	0.030332	m

Table 1.4.

D.Mesh

A uniform mesh sizing of 2 mm was employed throughout the computational domain to discretise the nozzle geometry. This mesh resolution was selected as a compromise between computational cost and solution accuracy, given the available computational resources. While a finer mesh could capture more detailed flow phenomena, such as boundary layer development and shock wave structures, the chosen mesh size was deemed adequate to resolve the primary flow features necessary for evaluating the performance variations across different nozzle geometries in this study.

IV. Solver and Physical Setup

This study employed a **density-based solver** in conjunction with the **Shear Stress Transport (SST) $k-\omega$ turbulence model** due to their effectiveness in resolving high-speed compressible flow with embedded shock structures and boundary layer interactions [20]. A **steady-state implicit formulation** was used throughout, as the flow remained relatively stable and convergence was reliably achieved under these conditions.

The simulation geometry was defined as **two-dimensional axisymmetric**, consistent with the physical characteristics of de Laval nozzles. The **energy equation** was enabled to account for compressibility and the coupling between static temperature and velocity fields [21][22]. Material properties for the exhaust gas were modeled using the **ideal gas law**, allowing density to vary as a function of pressure and temperature:

$$\rho = \frac{P}{RT} \quad (\text{eq.1.1})$$

To model viscosity, the **Sutherland Viscosity Law** was implemented, which adjusts viscosity based on temperature changes—a method widely validated in aerospace simulations [23]:

$$\mu = \frac{C_1 T^{3/2}}{T + C_2} \quad (\text{eq.1.2})$$

Values for specific heat and molecular weight were obtained via NASA's Chemical Equilibrium with Applications (CEA) outputs. Thermal conductivity was held constant, as its influence on pressure and momentum distributions was determined to be negligible.

Two primary simulation environments were configured: one for **ground-based static firing** and another for **in-flight expansion** across multiple altitudes. Boundary conditions for the ground case included a **pressure inlet of 20 bar at 2430.6 K**, a **pressure outlet of 1.01325 bar**, and standard no-slip wall and symmetry axis conditions.

Named Selection	Type	Input
Nozzle Inlet	Pressure Inlet	20 bar, 2430.6 K
Far Field	Pressure Outlet	1.01325 bar, 288.15 K
Nozzle Wall	Wall (no-slip)	Stationary
Axis	Axis	Symmetry

Table 1.5. Boundary Conditions for Ground Case

For the **flight case**, conditions were adapted based on actual altitude data obtained from OpenRocket simulations. Far-field boundaries were set using **altitude-dependent temperature and pressure** from the U.S. Standard Atmosphere 1976 model [24], with velocity inlets and pressure far-fields varying accordingly.

Named Selection	Type	Input
Nozzle Inlet	Pressure Inlet	20 bar, 2430.6 K
Far Field (Left)	Velocity Inlet	251 m/s, altitude-dependent pressure/temp
Far Field (Top, Right)	Pressure Far-field	Mach 0.75, altitude-dependent inputs
Inner/Outer Nozzle Wall	Wall (no-slip)	Stationary
Axis	Axis	Symmetry

Table 1.6. Boundary Conditions for Flight Case

Altitude (km)	Gauge Pressure (bar)	Temperature (K)
0	1.01325	288.15

5	0.5405	255.7
10	0.2650	223.3
20	0.0548	216.7
30	0.0116	226.5
50	0.0011	270.7
70	0.0002	220.0
100	0.00003	210.0

Table 1.7. Flight Altitude Atmospheric Conditions

The numerical methods used in all simulations included the Roe-FDS flux scheme, known for its robustness in resolving discontinuities in compressible flows [19]. Second-order upwind discretization was applied for all primary variables to minimize numerical diffusion near shock structures [25]. Gradient reconstruction was performed using a least-squares cell-based method, and all simulations used a Courant number of 0.5 to balance convergence stability and solution speed.

Numerical Methods:

Parameter	Setting
Formulation	Steady-State, Implicit
Flux Scheme	Roe-FDS
Gradient Method	Least Squares Cell-Based
Flow Discretization	Second Order Upwind
Turbulent Kinetic Energy	Second Order Upwind
Specific Dissipation Rate	Second Order Upwind

Table 1.8. Numerical Methods

Initial flow fields were generated using **hybrid initialization**, which accelerated convergence compared to standard techniques. Each simulation was run for **250 steady-state iterations**, which proved sufficient for convergence based on residual drop and thrust stabilization.

A uniform **2 mm mesh resolution** was applied across all nozzle geometries. Although this mesh density did not fully resolve boundary layer details, it successfully captured essential flow structures such as Mach waves, shock interactions, and expansion fans, and provided consistent performance comparisons between geometries.

V. Results and Discussion

5.1 Converging Section Study

Converging half-angle variations between 13° and 18° significantly impact throat Mach number, pressure losses, and flow uniformity, with smaller angles offering smoother acceleration but longer nozzle lengths

Converging half-angles between 13° and 18° significantly influenced throat Mach number and pressure losses. Smaller angles (13° – 14°) provided smoother acceleration but required longer nozzle lengths. Larger angles (17° – 18°) showed minor boundary layer separation risk near the throat, as reported by Huzel and Huang [19], who emphasised that sharper converging profiles can amplify viscous losses.

These findings are consistent with experimental studies by Zucrow & Hoffman [22], who noted that moderate converging angles preserve total pressure while limiting boundary layer growth. CFD studies by Kim & Lee [21] and Gao et al. [18] similarly showed that throat flow uniformity decreases with higher convergence steepness, validating the present observations.

5.2 Diverging Section Study

Diverging half-angles between 28° and 32° strongly influence expansion efficiency and shock behavior, with 30° providing the optimal balance between thrust and flow stability.

Diverging half-angles from 28° to 32° affected expansion efficiency and shock formation. A 30° diverging angle achieved the best balance, minimising adverse pressure gradients while maintaining compact geometry. Research by Hagemann [10] corroborates these findings, noting that diverging angles beyond 35° dramatically increase separation and reduce effective thrust.

Studies by Nasuti and Onofri [9] and Stark et al. [16] also found that optimised diverging sections can mitigate side loads caused by asymmetric separation, a phenomenon observed in the present simulations at 32° .

5.3 Fixed Geometry for Altitude Variation

The selected $15^\circ/30^\circ$ geometry demonstrates varying performance across altitudes, transitioning from over-expanded flow at sea level to under-expanded flow at high altitudes.

The $15^\circ/30^\circ$ geometry was tested across altitudes from 0 to 100 km. At sea level, slight over-expansion caused a weak compression shock. At 100 km, as previously described by Ashford et al. [26] in their studies on nozzle start-up behaviour. At 30 km, the nozzle was nearly ideally expanded, while at 100 km, under-expansion led to plume widening and efficiency loss, consistent with observations by Stark et al. [16] and Ivanco [17] on altitude-dependent expansion.

5.4. Geometry and Design Considerations

The selected converging and diverging angle ranges were grounded in literature and preliminary test results that identified them as the most promising for small-scale chemical

rockets. Subtle changes in these angles had noticeable effects on flow development: even a 1° increase in diverging angle shifted the shock position closer to the throat and introduced local adverse pressure gradients. The final expansion ratio of 3.365, determined from throat and exit area calculations (Eq. 3.13), is optimised for near sea-level and low-altitude operations, although it begins to under-expand at higher altitudes. These choices reflect a compromise between structural compactness and efficient expansion across most of the operational envelope.

5.5. Flow Physics Observations

CFD visualisations revealed that larger diverging angles (32°) increased internal separation risks and oblique shocks. Expansion fans dominated at high altitudes, while compression waves appeared near the exit at low altitudes. These trends agree with White [23], who analysed shock-boundary layer interactions, and numerical results from Menter [20] that confirmed SST $k-\omega$'s capability to capture such phenomena.

5.6. Altitude Simulation Results

Each simulated outlet pressure represented a specific altitude, allowing clear comparisons between plume behaviour and ambient conditions. At sea level (1.01325 bar), the nozzle showed slightly over-expanded flow, with compression shocks near the exit. By 30 km, the flow became perfectly expanded, showing no visible shocks in the exhaust. At 70–100 km, the nozzle operated in an under-expanded regime, with expansion fans extending from the nozzle lip. The plume widened significantly, and exit pressure remained far above ambient, causing potential efficiency loss. These transitions reflect how back pressure influences expansion and thrust, reinforcing the importance of designing for a mission-specific altitude.

5.7. CFD Mesh and Numerical Treatment

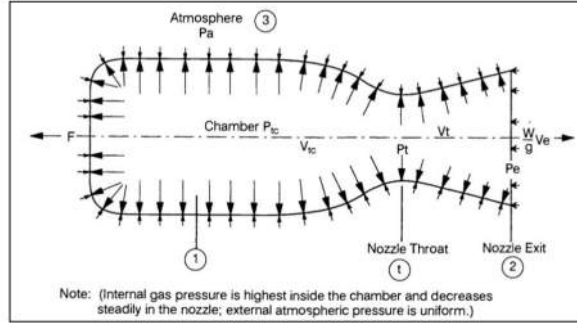
Due to computational limitations, a uniform mesh size of 2 mm was applied to all geometries. This resolution was sufficient to resolve primary flow structures such as Mach waves, shock formations, and expansion fans while ensuring reasonable convergence times. Although the mesh did not resolve detailed boundary layer profiles near the wall, it provided consistent comparative performance between geometries. Residual convergence was tracked through mass flow and pressure monitors, and 250 steady-state iterations were performed for each case. No explicit limiter schemes or shock-capturing enhancements were necessary due to the use of the Roe-FDS flux scheme and second-order discretisation.

5.8. Performance Analysis

Thrust was computed using a combination of momentum and pressure integrals at the nozzle exit, following the standard control volume approach:

$$(eq.1.3)$$

$$F = \dot{m}V_e + (p_e - p_a)A_e$$



The thrust efficiency was calculated relative to the theoretical isentropic maximum. Among all configurations, the 15°–30° geometry exhibited the highest thrust efficiency across most altitudes. This can be attributed to its ability to maintain attached flow, achieve near-ideal expansion in the mid-atmosphere, and avoid excessive divergence losses. Efficiency began to drop sharply at high altitudes due to increasing under-expansion losses and plume over-dispersion.

VI. Conclusion

Research on nozzle geometry highlights its critical influence on flow separation, shock structures, and propulsion efficiency [27][28]. Building on this foundation, our study demonstrates that even small variations in converging and diverging half-angles significantly impact flow behavior and performance across altitude ranges, aligning with reviews that emphasize the trade-offs between nozzle compactness and efficiency [29]. A 15° converging half-angle combined with a 30° diverging half-angle delivered the best balance between compact design and minimal shock losses, consistent with recent CFD and experimental findings on optimal nozzle performance [30]. While no single geometry is universally optimal, these results underscore the importance of tailoring nozzle configurations to mission-specific altitude conditions. Future work should explore adaptive or altitude-compensating nozzle concepts, finer mesh refinement, and transient simulations to capture the unsteady startup effect.

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The Impact of the 2011 NATO Libya Intervention on Global South Perceptions of the Responsibility to Protect

By Riya Ranade

ABSTRACT

This paper analyzes how the 2011 NATO intervention in Libya affected Global South views of the Responsibility to Protect (R2P) doctrine. NATO's military action in Libya, justified under R2P, went beyond civilian protection to ultimately overthrow Muammar Gaddafi's regime. On the one hand, this created distrust among many non-Western nations. On the other hand, it also led to an evolution of the norm. Many Global South states continued to endorse the principle's first two pillars of prevention and assistance. Their subsequent caution was focused on the use of military force under pillar three, which led to a more cautious and politically contested evolution of the norm. This study compares Global South attitudes toward R2P in four cases, including one before 2011: Sudan (2006), Libya (2011), Syria (2012), and Myanmar (2017). Results show divided responses: while Russia and China rejected R2P more strongly after Libya, they proposed reforms or continued to support the principle of protecting civilians in the future. The paper concludes that Libya weakened but didn't destroy R2P, as some Global South countries still sought to improve rather than abandon the doctrine.

KEYWORDS

Responsibility to Protect (R2P), Libya, NATO, State Sovereignty, UN Security Council

INTRODUCTION

The Responsibility to Protect (R2P) norm emerged in the early 2000s and was formally adopted at the 2005 World Summit after mass atrocities in Rwanda and Srebrenica occurred without any intervention. R2P aimed to prevent atrocities by setting up the expectation that a state should intervene when another fails to protect its own citizens.¹ The most famous application of R2P was in 2011 with the NATO-led intervention in Libya, which changed how the international community viewed R2P. Western powers tended to deem Libya a successful application of R2P since it prevented a massacre in Benghazi.² However, many states within the Global South were much more skeptical; critics like Russia and China accused NATO of overstepping UN Security Council Resolution 1973, which only authorized a no-fly zone and civilian protection but not regime change.³ This backlash reflected a fading trust in Western-led interventions and raised pressing questions about R2P's credibility. At the same time, in response to these concerns, alternative proposals were introduced, such as Brazil's Responsibility While

¹ Global Centre for the Responsibility to Protect, "What Is R2P?" Accessed August 14, 2025, <https://www.globalr2p.org/what-is-r2p/>.

² Teimouri, H., and S. P. Subedi, "Responsibility to Protect and the International Military Intervention in Libya in International Law: What Went Wrong and What Lessons Could Be Learned from It?" *Journal of Conflict and Security Law* 23, no. 1 (2018): 3–32. <https://doi.org/10.1093/jcsl/kry004>.

³ Tiyanjana Maluwa, "Stalling a Norm's Trajectory?: Revisiting U.N. Security Council Resolution 1973 on Libya and Its Ramifications for the Principle of the Responsibility to Protect," *California Western International Law Journal* 53 (2023): 69–46. https://insight.dickinsonlaw.psu.edu/fac_works/468.

Protecting (RWP). RWP highlighted stricter criteria for intervention, more involvement by the Security Council, and military action that is proportional to the conflict.⁴ This reflected a more balanced perspective on R2P; it was an attempt to align R2P with principles of sovereignty and independence.

The Libya intervention emphasized key questions about R2P, such as who decides when intervention is necessary, what are the limits and boundaries set on these interventions, and how to ensure accountability. What's unexpected is that, while it is widely assumed that the situation led to an overwhelming rejection of R2P, the reality is significantly more complicated. Some Global South nations became outspoken critics, seeking additional limits on its use, while others continued to be cautiously supportive, particularly in situations when mass crimes were glaring. This variation calls into question the oversimplified idea that the Global South consistently opposes "Western-led" humanitarian assistance. Therefore, this paper asks the following question: how did non-Western UN member states' perceptions of the Responsibility to Protect (R2P) doctrine change after the 2011 Libya intervention? Did the intervention diminish support for R2P among Global South states across the board, or did it lead in some cases to new ways of thinking about humanitarian intervention?

I argue that after Libya, the Global South did not unanimously turn against R2P but had diverse reactions. Following the 2011 Libya intervention, the Global South's attitude to R2P varied from outright resistance to progressive reforms. Some states, like Russia and China, grew more opposed and vetoed R2P entirely, whereas others, like Brazil and African countries, proposed reforms such as "Responsibility While Protecting" (RWP) or regional intervention.⁵ Several years later, international responses to Myanmar demonstrated a partial recovery of R2P legitimacy through non-military means like accountability and humanitarian access. This variety shows that while Libya did somewhat damage R2P's credibility, it also inspired efforts to change the norm to eliminate its flaws. Overall, Global South governments strongly modified R2P to strike a balance between atrocity prevention, sovereignty, and postcolonial concerns.

LITERATURE REVIEW

This argument both builds on and critiques existing scholarship. Most research focuses on Western perspectives or views the Global South as a monolith that entirely rejected R2P after the Libya intervention. Iain Attack (2002) explores the ethical issues of intervention, specifically the violation of sovereignty and the risk of militaristic goals of the intervening countries, which supports the fears that some states within the Global South have about Western abuse of power.⁶ Likewise, Gillian Brock (2007) argues that intervention should take consideration of sovereignty and human rights, ensuring that there are safeguards present to prevent abuse of the norm.⁷

⁴ Footnote missing https://www.files.ethz.ch/isn/165021/saia_sop_138_GPA_almeida_20130510.pdf

⁵ Teitt, Sarah. 2008. China and the Responsibility to Protect. Asia-Pacific Centre for the Responsibility to Protect. https://r2pasiapacific.org/files/451/china_and_r2P_2008_report.pdf.

⁶ Graham Long, "Humanitarian Intervention and the Responsibility to Protect: Who Should Intervene? By James Pattison," *Global Discourse* 2, no. 1 (2011): 209–212, accessed August 20, 2025, <https://doi.org/10.1080/23269995.2011.10707900>.

⁷ Gillian Brock, *Global Justice: A Cosmopolitan Account* (Oxford: Oxford University Press, 2009).

Nevertheless, Aidan Hehir (2008) examines how Libya damaged R2P's legitimacy but acknowledges how some states (like Brazil) wanted to edit the norm to be more successful.⁸ This agrees with the criticism about the misuse of R2P in Libya, emphasizing the need for clear guidelines. In contrast, the RWP concept paper (2011) by Brazil presents reforms to R2P, such as more strict oversight in an effort to adapt and change the norm to be more beneficial rather than abandon it completely.⁹ However, Daniel Fiott (2013) navigates how Libya confirmed fears of hypocrisy in humanitarian issues and critiques intervention.¹⁰ Similarly, Rosemary Foot (2021) discusses how R2P was abandoned in cases such as Xinjiang, showing that powerful countries can evade accountability, which can encourage skepticism within the Global South about the effectiveness of R2P.¹¹

In sum, scholarship on the post-Libya international environment generally agrees that the intervention damaged R2P's legitimacy among non-Western states. Daniel Fiott, Rosemary Foot and Aidan Hehir directly critique the intervention, stating that it confirmed fears about Western interventionism, causing it to be "abandoned" later on.¹² However, what is missing in any of these sources is an acknowledgment of regional differences among Global South states and what drives them. In other words, what remains undiscussed are the specific regional and ideological causes for their responses to the Libyan intervention, why certain regions or countries formed the opinions that they did, and the factors that shaped these views. This paper will fill that gap by examining the reason for R2P's complex global reception and delving into what those complexities were.

METHODS AND MATERIALS

To answer the research question above, this paper conducts comparative case study analysis. Specifically, I examine the following cases: Sudan 2006, Libya 2011, Syria 2012 and Myanmar 2017. These four were chosen to capture different phases of the challenges regarding R2P: Sudan 2006 shows an early interaction of R2P by the African Union; Libya 2011 is a crucial example of military intervention through R2P leading to controversy; Syria 2011-12 shows the security council at a standstill, leading to debates about R2P's limits; and Myanmar 2017 shows an example of a situation where R2P was not used and the damage it caused, allowing us to compare whether invoking R2P will cause less or more damage.

These case studies draw on three sources of data. First, I primarily analyze primary UN documents such as official General Assembly debates and Security Council meeting transcripts

⁸ Aidan Hehir and Robert W. Murray, eds., *Libya, the Responsibility to Protect and the Future of Humanitarian Intervention* (London: Palgrave Macmillan, 2013).

⁹ United Nations General Assembly, A/66/551, November 11, 2011, <https://docs.un.org/en/A/66/551>.

¹⁰ Daniel Fiott, "The Use of Force and the Third Pillar," in *The Responsibility to Protect and the Third Pillar*, 130–45, 2015, https://doi.org/10.1057/9781137364401_9.

¹¹ Rosemary Foot, "R2P Sidelined: The International Response to China's Repression of Muslim Minorities in Xinjiang," *Global Responsibility to Protect* 13, no. 1 (2021): 29–32, <https://doi.org/10.1163/1875-984x-13010005>.

¹² Fiott, "The Use of Force and the Third Pillar."

between 2009 and 2012. Specifically, I analyze speeches given by diplomats during key moments in time in the four cases above. These speeches will be explored to understand the values, rhetoric and concerns shaping these countries' perceptions of R2P, with an emphasis on regional differentiation. I specifically look for language around "non-interference" or "state consent" as well as explicit reference to R2P within their arguments.

Second, I evaluate UN voting records from the same time period to track how positions on R2P evolved and differed within the Global South. Voting patterns on key moments such as Resolution 1706 and Resolution 1973 will be compared across regions to determine the support or rejection of the norm. This includes Brazil's proposal of RWP and the more oppositional stances from China and Russia, who frequently vetoed R2P. By mapping and displaying these patterns, this helps highlight how different Global South countries navigated the complexity of R2P. To fill the gaps left by limitations in the primary sources, my research will use a range of secondary sources to contextualize and interpret the trends in states' positions. Finally, I consult academic articles, policy papers, and reports analyzing the varied impact of Libya 2011 on R2P in Sudan, Myanmar, and Syria to support these primary sources. This multi-method approach helps develop a nuanced understanding of the issues with R2P and the impact of Libya 2011.

There are several limitations to these data sources. First, relying on public UN records can pose a challenge, since closed-door conversations and private negotiations might be key to the research. Accordingly, using only public records may create a gap in the research material. I mitigate this by supporting my primary sources via secondary sources to ensure balance and depth of knowledge. Second, sources mainly from Western perspectives can pose an issue since they may have some inherent bias and not showcase the perceptions of the Global South, which is the focus of this paper. To mitigate this, I mindfully curate a list of sources that are diverse in origin, including from non-Western scholars.

WHAT IS RESPONSIBILITY TO PROTECT?

R2P is a norm that redefines sovereignty as a responsibility rather than a right. It originated in the early 2000s after the international community failed to react to issues in Rwanda and Srebrenica.¹³ The International Commission on Intervention and State Sovereignty (ICISS) established R2P by including the concept in their 2001 report, explaining that states must protect their populations and that UN member states have a duty to intervene when they fail.¹⁴ At the 2005 World Summit, R2P was adopted by UN member states, and they focused on three aspects of R2P: a state has a responsibility to protect its own citizens, the international community must help a state to have the capacity to protect its citizens, and timely intervention when atrocities occur.¹⁵ R2P is not a legal norm, though it is grounded in international law and

¹³ Global Centre for the Responsibility to Protect, "What is R2P?"

¹⁴ International Commission on Intervention and State Sovereignty (ICISS), *The Responsibility to Protect: Report of the International Commission on Intervention and State Sovereignty* (Ottawa: International Development Research Centre, December 2001).

¹⁵ Halliyadde, "The Meaning of the Responsibility to Protect."

based on the provisions of the UN charter.¹⁶ However, R2P cannot be enforced; its application relies on the political will of countries, leading to its problematic nature.

The adoption of R2P in 2005 was significant because it supported the idea that sovereignty is not a right but rather something that depends on a state's ability and willingness to protect its people, challenging more traditional norms of non-intervention in the internal affairs of sovereign states. This shift was welcomed, particularly after the Cold War, when human rights concerns gained global prominence.¹⁷ However, the norm implementation was ambiguous, as it sought to achieve a balance between human rights and state sovereignty. R2P was based on "three pillars" of responsibility (state responsibility, international assistance and international action): some states, specifically Western democracies, focused on the third pillar concerning coercive action, arguing that it was a moral obligation to intervene.¹⁸ In contrast, a majority of Global South states focused on the first two pillars, viewing external military action as an extreme.¹⁹ This tension and disagreement was exemplified after 2011, highlighting R2P's issues.

As a result of its aspirational nature, R2P has faced opposition and challenges that have significantly reduced its effectiveness in preventing atrocities. Its most major criticism was that the interventions that R2P supports are often motivated by selfish geopolitical interests.²⁰ The norm's reliance on Security Council authorization has also posed an issue, since the veto-wielding permanent members can block any intervention. Additionally, the absence of a clear definition of what warrants intervention has led to unclear and hazy boundaries about when R2P should be applied.²¹ These limitations have led scholars to argue that R2P is idealistic and less grounded in reality and is difficult to enforce due to its issues in clarity.

It is important to emphasize that R2P is often, if not exclusively, viewed as enabling military intervention; this interpretation is too strict and ignores the doctrine's bigger, complex framework. R2P is essentially a preventative and protective strategy designed to help countries in satisfying their responsibilities to protect their people against genocide, war crimes, ethnic cleansing, and crimes against humanity.²² Military action is only considered a last resort, the final step after all diplomatic, humanitarian, and nonviolent options have been explored. In practice, R2P includes a variety of non-military tactics, including advanced warning systems, diplomatic pressure, sanctions, public condemnation, humanitarian aid coordination, and international inquiries or fact-finding missions.²³

¹⁶ ICISS, *The Responsibility to Protect*.

¹⁷ "Responsibility to Protect," in *Encyclopedia of Public International Law* (Oxford: Oxford University Press), <https://opil.ouplaw.com/display/10.1093/law:epil/9780199231690/law-9780199231690-e1464>.

¹⁸ Global Centre for the Responsibility to Protect, "What Is R2P?"

¹⁹ Ibid.

²⁰ Dawson Grant, "'No Future for Libya with Gaddafi': Classical Realism, Status and Revenge in the UK Intervention in Libya," *Cambridge Review of International Affairs* (2021): 1–18, <https://www.tandfonline.com/doi/full/10.1080/09557571.2021.1888879>.

²¹ Roland Paris, "The 'Responsibility to Protect' and the Structural Problems of Preventive Humanitarian Intervention," *International Peacekeeping* 21, no. 5 (October 2014): 569–603, <https://www.tandfonline.com/doi/full/10.1080/13533312.2014.963322>.

²² Global Centre for the Responsibility to Protect, "What Is R2P?"

²³ Jared Genser, "The United Nations Security Council's Implementation of the Responsibility to Protect: A Review of Past Interventions and Recommendations for Improvement," *Chicago Journal of International Law* 18 (2018), <https://cjl.uchicago.edu/print-archive/united-nations-security-councils-implementation-responsibility-protect-review-past>.

LIBYA AND THE CONTROVERSIES SURROUNDING R2P

The international intervention in Libya in 2011 was a key point in R2P's history. In 2011, the UN Security Council authorized a no-fly zone over Libya under Resolution 1973, utilizing R2P to justify military force against Muammar Qaddafi to protect civilians; it was the first time R2P was directly used to justify military intervention.²⁴ However, NATO intervention went beyond this mandate, creating a controversy about the misuse of R2P. While the intervention began with establishing a no-fly zone, it quickly became controversial because NATO actions actively supported regime change within Libya by providing air support to rebel forces and targeting military infrastructure²⁵.

This overreach sparked widespread criticism about R2P's misuse. In particular, many critics in the Global South argued that NATO exploited R2P for selfish purposes. The African Union, for instance, opposed the Libya intervention and exposed crucial issues within R2P. Since the AU was the body that was directly affected by Libya's destabilization, they criticized the disregard for regional opinion and inclusion in the decision-making about the Libya intervention. This criticism became popular since the impact of the Libyan intervention was felt throughout Africa, creating security and humanitarian issues throughout. The AU's stance reflected a broader concern about who decides when and how R2P is invoked and to what authority they must answer.²⁶

While the prevailing assumption among scholars is that this controversy led to a complete drop off of support for R2P, this approach is overly simplistic. In fact, specific regions and states within the Global South often reacted to the situation in Libya differently, some skeptically and some more supportively. Countries like India and South Africa, which were previously open to R2P, seem to have become much more cautious about supporting Western interventions.²⁷ The following section will analyze four case studies to illustrate how the Global South responded to atrocity crimes in four case studies, the first two occurring before the Libyan aftermath and the last two showcasing the impact of Libya on R2P.

DISCUSSION: GLOBAL SOUTH RESPONSE TO R2P

Sudan (2006)

Overview of the Crisis in Sudan, 2003-2006

The 2006 crisis in Darfur, Sudan, was one of the earliest significant tests of R2P after its adoption in the 2005 World Summit. The responses by the Global South at this particular moment in time were complicated; countries were often skeptical, concerned about sovereignty,

²⁴ United Nations Security Council, *S/RES/1973 (2011)*, March 17, 2011, [https://docs.un.org/S/RES/1973%20\(2011\)](https://docs.un.org/S/RES/1973%20(2011)).

²⁵ Dina Mansour-Ille, "Libya's Political Crisis: A Legacy of Failed Interventionism," PRISME Initiative, June 11, 2024, <https://prismeinitiative.org/publications/libyas-political-crisis-dina-mansour-ille/>.

²⁶ Christian Wyse, "The African Union's Right of Humanitarian Intervention as Collective Self-Defense," *Chicago Journal of International Law* 19, no. 1 (2018): 295–332.

²⁷ Vikash Chandra, "Explaining India's Approach to Responsibility to Protect," *Jadavpur Journal of International Relations* 25, no. 2 (2021): 187–207, <https://doi.org/10.1177/09735984211043052>.

and influenced by colonial memory. The Darfur case was how the Global South's individual opinions on the R2P norm were brought to light.

The Darfur crisis began in early 2003 when the Sudan Liberation Army (SLA) and the Justice and Equality Movement (JEM), which represented minority ethnic groups, launched rebellions in Khartoum, wanting inclusion and protection.²⁸ In response, the Sudanese government used Arab militias (such as the Janjaweed) to carry out massacres, rape and village burnings, forcing the displacement of the aforementioned minority groups.²⁹ The situation escalated into what the Human rights watch called an ethnic cleansing and crimes against humanity.³⁰ By the middle of 2004, hundreds of villages were destroyed, and many had fled. Humanitarian Aid agencies cautioned about a famine if action was not taken,³¹ The international community grew concerned as the AU and the UN were struggling to respond. The AU deployed AMIS in mid-2004 and kept expanding the number of troops till 2005. The mission failed since it was underfunded and faced obstacles from the Sudanese government.³² By 2005, the death toll was over 200,000 and 2 million people were displaced; the US officially deemed it a genocide, creating more pressure for the international community to act.³³

Global South Attitudes Pre-R2P, 2003-2005

From the beginning, the Global South's response to Darfur was heavily influenced by giving importance to sovereignty. The African Union (AU) was central in responding to the Darfur crisis through its peacekeeping force AMIS.³⁴ While the AU were generally supportive of the protection of civilians, they were cautious of fully supporting R2P since it allowed foreign intervention without the state's consent. AMIS was seen as an "African solution to an African problem," a phrase that emphasized the African Union's stance on maintaining regional control over the response while respecting Sudan's sovereignty.³⁵ The AU mainly wanted to balance appeasing the international community and respecting African states' sovereignty and was extremely cautious of setting a precedent that could potentially justify foreign intervention in

²⁸ United Nations, "Explainer: How Darfur Became a 'Humanitarian Calamity and Catastrophic Human Rights Crisis,'" UN News, December 2023, <https://news.un.org/en/story/2023/12/1144787#:~:text=Although%20Darfur%20has%20experienced%20intermittent,between%20the%20paramilitary%20Rapid%20Support>

²⁹ Human Rights Watch, *Darfur Destroyed: Ethnic Cleansing by Government and Militia Forces in Western Sudan* (New York: Human Rights Watch, May 2004), <https://www.hrw.org/report/2004/05/06/darfur-destroyed/ethnic-cleansing-government-and-militia-forces-western-sudan>.

³⁰ Human Rights Watch, "World Report 2006 - Introduction: Darfur and the African Union," <https://www.hrw.org/legacy/wr2k6/introduction/10.htm>.

³¹ AP News, "Russia Vetoes UN Resolution Calling for Immediate Cease-fire in the War Between Sudan's Rival Forces," November 19, 2024, <https://apnews.com/article/85e2b7bb49edc8ca104cf3b9a887c859>.

³² Samantha Power, "Missions," *The New Yorker*, November 21, 2005, <https://www.newyorker.com/magazine/2005/11/28/missions>.

³³ United States Holocaust Memorial Museum. "Darfur." In *Holocaust and Genocide Encyclopedia*.

³⁴ Al-Momani, Shaul. 2018. "The Responsibility to Protect and the Arab World: An Emerging Regional Policy?." *Journal of Public and International Affairs (JPJA)*, April 16, 2018. <https://jpia.princeton.edu/document/378>.

³⁵ UN News. "Security Council Votes to Set up UN Peacekeeping Force in Darfur," August 31, 2006. <https://news.un.org/en/story/2006/08/190582-security-council-votes-set-un-peacekeeping-force-darfur>

Africa.³⁶ The AU refused to endorse military action and preferred using diplomatic methods such as ceasefire negotiations conducted through Abuja and Addis Ababa.³⁷

To an even greater extent, Arab countries were highly skeptical of applying R2P in Sudan. The Arab League, specifically Egypt and Algeria, highlighted non-intervention and the importance of state sovereignty.³⁸ In speeches in the UN Security Council and regional discussions, Arab states commonly downplayed and trivialized the atrocities in Darfur, with Algeria stating, “We remain convinced that a coercive military operation would be counterproductive and could complicate the search for a political solution to the conflict and jeopardize the humanitarian operation already under way... My delegation is also concerned about the introduction of new concepts such as ‘the responsibility to protect’, which might be used to justify unauthorized enforcement actions.”³⁹ In an Arab league meeting, ministers wanted the international community to “reject any threat of military intervention,” wanting to give Sudan time to address the issue internally.⁴⁰ Arab countries were afraid that agreeing to the UN’s intervention could bring their own systems under scrutiny.

Among Asian states, the prevailing sentiment was against Western intervention. China was a poignant critic of intervention in Sudan, especially since it was Sudan’s largest oil investor and trading partner. China protected Khartoum from Security Council interference. China saw this as “unhelpful” and held the opinion that all measures must be taken within the Sudanese government; it firmly held the opinion that such matters should be handled through negotiation and ultimate respect for sovereignty⁴¹. Other Asian countries such as India and Pakistan held similar opinions; while they believed human rights were important, the principle of nonintervention felt like the safer stance to have.⁴² Along with China, India and Pakistan abstained on Resolution 1591 in March 2005, refusing sanctions and prioritizing discussion.⁴³ Their concern was if R2P was normalized, it could justify interference in their own affairs, such as in Kashmir or Balochistan.⁴⁴

³⁶ Wyse, Christian. “The African Union’s Right of Humanitarian Intervention as Collective Self-Defense.” *Chicago Journal of International Law* 19, no. 1 (2018): 295–332.

³⁷ European-Sudanese Public Affairs Council (ESPAC). 2007. *Darfur: The International Community's Betrayal*. London: ESPAC. <https://www.espac.org/pdf/Darfur-Book-New-Edition.pdf>.

³⁸ Boukhars, Anouar. 2020. “Algeria's Role in the Libya Conflict.” TRT World Research Centre, November 2020. https://researchcentre.trtworld.com/wp-content/uploads/2020/11/Algeria_Role_in_Libya.pdf.

³⁹ United Nations Security Council, S/RES/1706 (2006), August 31, 2006, <https://digitallibrary.un.org/record/543313>.

⁴⁰ “Arab League backs Sudan on Darfur.” Al Jazeera, August 8, 2004. <https://www.aljazeera.com/news/2004/8/8/arab-league-backs-sudan-on-darfur>.

⁴¹ Holslag, Jonathan. “China’s Diplomatic Maneuvering on the Question of Darfur.” *Journal of Contemporary China* 17, no. 54 (December 4, 2007): 71–84. <https://doi.org/10.1080/10670560701693088>.

⁴² “Speakers in Security Council Urge Balance Between UN Role in State Sovereignty and Human Rights Protection, but Differ Over Interpretation of Charter Principles | Meetings Coverage and Press Releases,” February 15, 2016. <https://press.un.org/en/2016/sc12241.doc.htm>.

⁴³ “China’s Diplomatic Maneuvering on the Question of Darfur.” *Journal of Contemporary China* 17, no. 54 (December 4, 2007): 71–84. <https://doi.org/10.1080/10670560701693088>.

⁴⁴ Raashed, Maryam. “Invoking Responsibility to Protect Doctrine in Jammu and Kashmir: Prospects and Challenges.” *Centre for Strategic and Contemporary Research*, August 21, 2024.

Global South Attitudes Post-R2P, 2005-2006

After 2005, many African countries shifted from cautious regional thinking to actively supporting more strong, R2P-aligned measures in Darfur. For example, with the launch of the African Union-United Nations Hybrid Operation in Darfur (UNAMID), African leaders highlighted the importance of civilian protection.⁴⁵ In a joint AU-UN briefing, the Secretary-General encouraged increased support, stating that “AU troops in Darfur have performed very well given the demanding conditions...we must all do our utmost to build on these significant contributions,” states the UN Press Secretary.⁴⁶ The message recognized African responsibility while encouraging foreign assistance. Nigerian authorities emphasized that neither the Sudanese government nor the African Union could manage the security responsibility alone and that the United Nations must play an important role in stabilizing the area.

The UN Security Council Resolution 1706, adopted at meeting S/PV.5519 on August 31st 2006 expanded UNMIS to Darfur and authorized 17,300 troops and 3,300 police officers to support the Darfur Peace Agreement, explicitly using R2P language by referencing the 2005 World Summit Outcome document, paragraphs 138-139.⁴⁷ The vote was 12 in favor and none against, with 3 abstentions from China, Russia and Qatar.⁴⁸ In the meeting, China declared that while they supported the resolution, they abstained since it lacked Sudanese consent, emphasizing that “such measures should be postponed until negotiation” and doubling down on the importance of sovereignty despite viewing the UN interference as a “realistic option” when consent was given.⁴⁹ Russia had similar reasoning, viewing the mandatory deployment as an interference without Sudan’s consent, while Qatar focused on principles of non-intervention and procedural legitimacy.⁵⁰ Ghana, which spoke for the African states, was more welcoming⁵¹ but expressed concern about Sudan’s agreement about the deployment, while they agreed about the urgency for civilian protection in Darfur⁵².

<https://cscpr.org/explore/themes/politics-governance/invoking-responsibility-to-protect-doctrine-in-jammu-and-kashmir-prospects-and-challenges/>.

⁴⁵ Schmidt, Annie. “Keeping Sudan in Focus: Policy Options for the Protection of Civilians.” International Peace Institute, June 30, 2025. <https://www.ipinst.org/?p=41136>.

⁴⁶ “IN MESSAGE TO AFRICAN UNION PEACE AND SECURITY COUNCIL, SECRETARY-GENERAL REITERATES CALL FOR IMMEDIATE, UNCONDITIONAL CESSATION OF HOSTILITIES IN DARFUR | Meetings Coverage and Press Releases,” November 30, 2006.

⁴⁷ UN News. “Security Council Votes to Set up UN Peacekeeping Force in Darfur,” August 31, 2006.

<https://news.un.org/en/story/2006/08/190582-security-council-votes-set-un-peacekeeping-force-darfur>. ; UN. Security Council (61st year : 2006). “Resolution 1706 (2006) /: Adopted by the Security Council at Its 5519th Meeting, on 31 August 2006.”

United Nations Digital Library System, August 31, 2006. <https://digitallibrary.un.org/record/582107> ; “SECURITY COUNCIL EXPANDS MANDATE OF UN MISSION IN SUDAN TO INCLUDE DARFUR, ADOPTING RESOLUTION 1706 BY VOTE OF 12 IN FAVOUR, WITH 3 ABSTAINING | Meetings Coverage and Press Releases,” August 31, 2006.

<https://press.un.org/en/2006/sc8821.doc.htm>.

⁴⁸ UN News. “Security Council Votes to Set up UN Peacekeeping Force in Darfur,” August 31, 2006.

<https://news.un.org/en/story/2006/08/190582-security-council-votes-set-un-peacekeeping-force-darfur>.

⁴⁹ United Nations Security Council, S/PV.5519 (2006), September 20, 2006, <https://docs.un.org/en/S/PV.5519>.

⁵⁰ United Nations Security Council, S/PV.5519 (2006), September 20, 2006, <https://docs.un.org/en/S/PV.5519>.

⁵¹ United Nations Security Council, S/PV.5519 (2006), September 20, 2006, <https://docs.un.org/en/S/PV.5519>.

⁵² UN News. “Security Council Votes to Set up UN Peacekeeping Force in Darfur,” August 31, 2006.

<https://news.un.org/en/story/2006/08/190582-security-council-votes-set-un-peacekeeping-force-darfur>.

To begin with, the abstentions by China, Russia, and Qatar showcased that there was general support for R2P with the condition of consent.⁵³ Their statements within discussions showed that they wanted R2P to be more than a justification for foreign intervention but rather a concept that worked with respect for sovereignty. African representatives (through Ghana) prioritized regional leadership and AU ownership; they wanted the AU to be the primary actor in the crisis in Darfur. They were extremely against any hint of the UN suggesting to bypass Sudanese or African consent, highlighting the early skepticism from the Global South of external intervention. The Global South's stances in 2006 were complex; they accepted the concept of international civilian protection but were hesitant or outright refused to bypass regional legitimacy and Sudanese consent.

In conclusion, the Darfur crisis of 2003–2006 emphasized a guarded and evolving perspective of the Responsibility to Protect (R2P) among the Global South. Between 2003 and 2005, most Global South states were cautious of the norm, viewing it as a possible tool for Western interference that threatened state sovereignty and expressed the legacy of colonialism. Their responses highlighted regional solutions, such as AMIS, and repeatedly rejected military intervention without host-state permission. However, by 2006, once R2P was formally accepted at the UN World Summit, their opinions began to alter gradually. Overall, while the Global South did not fully embrace R2P during the Sudan crisis, their stance changed from outright skepticism to a more restricted acceptance, highlighting an early tension between protection of humans and sovereignty that would influence Global South engagement with R2P in future crises.

Libya (2011)

Overview of the Crisis in Libya, 2011

The 2011 NATO-led intervention in Libya, which was authorized under the United Nations' Responsibility to Protect (R2P) norm, is still one of the most controversial applications of the principle.⁵⁴ Even though the immediate justification was to protect civilians from Muammar Gaddafi's violent repression of protesters, many countries, particularly in the Global South, saw the intervention as setting a dangerous precedent.⁵⁵ Their response reveals deep divisions over R2P, driven by concerns about sovereignty, Western dominance, and the potential abuse of humanitarian norms.

The Libyan uprising began in February 2011, as part of the larger Arab Spring. Protesters in Benghazi and Tripoli wanted political freedom and an end to Muammar Gaddafi's 42-year rule.⁵⁶ Gaddafi's regime responded with lethal force; troops opened fire on peaceful protestors,

⁵³United Nations General Assembly, A/78/PV.99 (2024), March 1, 2024, <https://docs.un.org/en/A/78/PV.99>.

⁵⁴Carati, Andrea. "Responsibility to Protect, NATO and the Problem of Who Should Intervene: Reassessing the Intervention in Libya." *Global Change Peace & Security* 29, no. 3 (September 2, 2017): 293–309. <https://doi.org/10.1080/14781158.2017.1384719>.

⁵⁵BBC News. "Libya: UN Backs Action Against Colonel Gaddafi," March 18, 2011. <https://www.bbc.com/news/world-africa-12781009>.

⁵⁶"Libya Revolt of 2011 | History, War, Timeline, & Map." *Encyclopedia Britannica*, April 14, 2011. <https://www.britannica.com/event/Libya-Revolt-of-2011>.

killing over 100 people in 3 days in Benghazi.⁵⁷ The ICC prosecutor estimated 500-700 deaths by the end of February, establishing that war crimes were committed in the process.⁵⁸ On February 20th, Gaddafi delivered a speech threatening “thousands of deaths, rivers of blood,” promising to cleanse Libya “room by room” and “fight to the last man, the last woman, the last bullet” if protests were to continue.⁵⁹ These statements were extremely concerning for the international community, as they used genocidal language and promised further violence and death.⁶⁰ By late February, cities were under fire and civilian areas were targeted, urging international intervention.

Global South Attitudes Pre-Intervention, February-March 2011

In response to the violence, the UNSC adopted Resolution 1970 on February 26, 2011.⁶¹ The resolution-imposed sanctions, arms embargoes, and asset freezes and brought Gaddafi under investigation in the ICC.⁶² Statements made show there was widespread support for R2P; many countries in the Global South supported these resolutions, referring to the urgency of civilian protection, with Brazil stating, “We are deeply disturbed by the dramatic situation in Libya. The level of violence against the civilian population is totally unacceptable... The measures we are adopting today are meant to halt violence, ensure the protection of the civilian population, and promote respect for international law.”⁶³ African members of the Security Council supported sanctioning Gaddafi and supported both resolutions; they claimed that action was needed to stop mass killings and adhere to R2P logic, with South Africa stating, “South Africa remains deeply concerned at the deteriorating situation in Libya, which has resulted in untold atrocities and countless loss in civilian lives. ... We believe that the United Nations and the Security Council could not be silent, nor be seen to be doing nothing in the face of such grave acts of violence committed against innocent civilians.”⁶⁴

After several weeks, Gaddafi continued refusing to deescalate, and the UNSC decided to take more serious action, adopting Resolution 1973 in March, authorizing “all necessary measures,” including a no-fly zone and military strikes, to protect civilians.⁶⁵ Shortly afterward,

⁵⁷ Adetunji, Jo, and Peter Beaumont. “Libya Protests: More Than 100 Killed as Army Fires on Unarmed Demonstrators.” *The Guardian*, July 10, 2024. <https://www.theguardian.com/world/2011/feb/20/libya-protests-benghazi-muammar-gaddafi>.

⁵⁸ International Criminal Court. 2011. “Libya.” International Criminal Court. 2011. <https://www.icc-cpi.int/situations/libya>.

⁵⁹ son. 2011. “Gaddafi’s Son Warns of ‘Rivers of Blood’ in Libya.” العربية. February 21, 2011. <https://www.alarabiya.net/articles/2011%2F02%2F21%2F138515>.

⁶⁰ Campbell, Alicia. “The Language of Genocide.” *Harvard Political Review*, November 12, 2022. <https://harvardpolitics.com/the-language-of-genocide/>.

⁶¹ Global Centre for the Responsibility to Protect. “Resolution 1970 (Libya) S/RES/1970 - Global Centre for the Responsibility to Protect,” November 12, 2019. <https://www.globalr2p.org/resources/resolution-1970-libya-s-res-1970/>.

⁶² United Nations Security Council, S/RES/1970 (2011), February 26, 2011, <https://www.un.org/securitycouncil/content/resolutions>.

⁶³ “In Swift, Decisive Action, Security Council Imposes Tough Measures on Libyan Regime, Adopting Resolution 1970 in Wake of Crackdown on Protesters | Meetings Coverage and Press Releases,” February 26, 2011. <https://press.un.org/en/2011/sc10187.doc.htm>.

⁶⁴ United Nations Security Council, S/PV.6491 (2011), February 26, 2011, <https://www.securitycouncilreport.org/atf/cf/%7B65BFCF9B-6D27-4E9C-8CD3-CF6E4FF96FF9%7D/Libya%20S%20PV%206491.pdf>.

⁶⁵ United Nations Security Council, S/RES/1973 (2011), March 17, 2011, <https://www.un.org/securitycouncil/content/resolutions>.

NATO states imposed a no-fly zone over Libya. Before the vote, South Africa called for an end to the use of force in Libya and supported the resolution in its message to Libya to end the violence by stating, “This unanimous resolution sends a clear and unambiguous message to the Libyan authorities to end the carnage against their people... South Africa calls on the Government and people of Libya to seek a speedy and peaceful resolution to the current crisis, in accordance with the will of the Libyan people.”⁶⁶ In meeting SPV.6498 on March 17th, the Security Council explicitly discussed civilian protection using R2P language. For example, France noted, “we must not abandon civilian populations, the victims of brutal repression, to their fate; we must not allow the rule of law and international morality to be trampled underfoot.”⁶⁷ The United States added by stating, “For weeks, the world has watched with alarm as the Qadhafi regime carried out a premeditated campaign of murder and persecution... His forces have been unleashed upon the people of Libya... This is a violation of every standard of international conduct and a violation of common decency.”

Notably, India, Brazil, Russia, Germany, and China abstained on Resolution 1973. India specifically stated “uncertain information on the ground” and a lack of clarity on what enforcement would entail. They did not outright reject the resolution but wanted to be cautious about the open-ended language of “all necessary measures.”⁶⁸ Similarly, China did not want to give permission for Western powers to intervene with no regulation but recognized the urgency of the situation in Libya.⁶⁹

This showcases that generally, at this point in time, the international community was largely in favor of R2P and invoking it to prevent atrocities. Libya’s early referral to the International Criminal Court, as well as the fast approval of UN Security Council Resolution 1973, which allowed “all necessary measures” to protect people, were unusual. Key votes from non-permanent Security Council members such as South Africa, Nigeria, Gabon, and Lebanon indicated strong, albeit conditional, support for the R2P idea among the Global South. This was regarded as a watershed event, demonstrating that a wide coalition, including big developing countries, could band together to take action against a dictatorship that threatened its own people.

Global South Attitudes Post-Intervention, March 2011 Onward

By pushing for a no-fly zone, the Arab League helped to legitimize NATO’s activities at the very beginning. However, this support from Arab states decreased over time.⁷⁰ Countries like Lebanon, which proposed the Human Rights Council resolution suspending Libya, first saw participation as necessary to defend people. Others, especially Syria and Algeria, opposed

⁶⁶United Nations Security Council, S/PV.6491 (2011), February 26, 2011, <https://www.securitycouncilreport.org/atf/cf/%7B65BFCF9B-6D27-4E9C-8CD3-CF6E4FF96FF9%7D/Libya%20S%20PV%206491.pdf>.

⁶⁷Deen, Thalif, and Truthout. “UN Body Authorizes Military Intervention in Libya.” Truthout, March 18, 2011. <https://truthout.org/articles/un-body-authorizes-military-intervention-in-libya/>.

⁶⁸United Nations General Assembly, A/RES/60/1 (2005), October 24, 2005, <https://digitallibrary.un.org/record/699777>.

⁶⁹ “China’s Balancing Act in Libya.” 2020. Carnegieendowment.org. 2020. <https://carnegieendowment.org/posts/2020/05/chinas-balancing-act-in-libya?lang=en>.

⁷⁰ Alaalidin, Ranj. 2016. “Libya & the Arab League.” Political Rationale and International Consequences of the War in Libya, April, 105–17. <https://doi.org/10.1093/acprof:oso/9780198767480.003.0006>.

Western intervention, warning that Libya was becoming a puppet for international interests.⁷¹ The Arab countries' discomfort rose as the bombing campaign intensified and photos of Gaddafi's death spread. The concern changed from human rights to sovereignty and stability. Libya's focus shifted from civilian protection to regime change, leaving several Arab states regretting their early assistance.⁷²

African countries criticized how the event was carried out. Despite first condemning Gaddafi's atrocities and suspending Libya's membership, the African Union (AU) eventually showed significant disapproval of NATO's military intervention.⁷³ South Africa, Nigeria, and Gabon all voted for Resolution 1973, but later expressed disappointment that it was seen as a green light for regime change.⁷⁴ The African Union had initially proposed a negotiated political solution, sending a High-Level ad hoc Committee to mediate between Gaddafi and the rebels, but this effort was largely sidelined by NATO's swift escalation of military operations.⁷⁵ South Africa's President Jacob Zuma later criticized NATO for ignoring the AU's roadmap for peace, stating that "we strongly believe that the resolution is being abused for regime change, political assassinations and foreign military occupation." South African President Jacob Zuma was outspoken in his condemnation, accusing NATO of hijacking the resolution.⁷⁶ Zuma said that the West has hijacked the rhetoric of R2P to pursue its own interests, ignoring Africa's need for peaceful settlement.⁷⁷ The AU Peace and Security Council declared that NATO's interpretation "went far beyond the mandate" of safeguarding people, decreasing the legitimacy of international norms.

Asian governments, like India and China, were highly skeptical about R2P's implementation in Libya. Both abstained from voting on Resolution 1973.⁷⁸ India brought up major concerns about the resolution's unclear phrasing and warned against its potential abuse. Later, Indian authorities opposed the NATO campaign for going beyond the resolution's scope and compromising Libyan sovereignty.⁷⁹ China was wary. While Beijing did not oppose the

⁷¹ Bronner, Ethan, and David E. Sanger. 2011. "Arab League Endorses No-Flight Zone over Libya." *The New York Times*, March 12, 2011, sec. World. <https://www.nytimes.com/2011/03/13/world/middleeast/13libya.html>.

⁷² Security Council Report. "Cross-Cutting Report No. 2: Protection of Civilians," n.d. https://www.securitycouncilreport.org/research-reports/lookup_c_glkwlemtisg_b_7566867.php#:~:text=The%20Council%20subsequently%20authorised%20the,to%20stop%20violence%20against%20civilians.

⁷³ Adams, Simon and Global Centre for the Responsibility to Protect. "Libya and the Responsibility to Protect." Global Centre for the Responsibility to Protect Occasional Paper Series, October 2012.

<https://www.globalr2p.org/wp-content/uploads/2020/07/LibyaAndR2POccasionalPaper.pdf>.

⁷⁴ United Nations. "Repertoire of the Practice of the Security Council, 2010-2011," 2011.

https://main.un.org/securitycouncil/sites/default/files/en/sc/repertoire/2010-2011/Part%20I/2010-2011_Libya.pdf.

⁷⁵ ACCORD. "The 2011 Libyan Crisis—ACCORD," December 5, 2017.

<https://www.accord.org.za/conflict-trends/2011-libyan-crisis/>.

⁷⁶ Kirchick, James. "South Africa Stands With Qaddafi." *The Atlantic*, September 6, 2011.

<https://www.theatlantic.com/international/archive/2011/09/south-africa-stands-with-qaddafi/244584/>.

⁷⁷ Adams, Simon. 2012. "Libya and the Responsibility to Protect Global Centre for the Responsibility to Protect Occasional Paper Series."

<http://www.globalr2p.org/wp-content/uploads/2020/07/LibyaAndR2POccasionalPaper.pdf>.

⁷⁸ Chandra, Vikash. "Explaining India's Approach to Responsibility to Protect." *Jadavpur Journal of International Relations* 25, no. 2 (September 13, 2021): 187–207. <https://doi.org/10.1177/097359842111043052> . ;

https://elibrary.law.psu.edu/cgi/viewcontent.cgi?article=1471&context=fac_works

⁷⁹ Nuruzzaman, Mohammed. 2022. "'Responsibility to Protect' and the BRICS: A Decade after the Intervention in Libya." *Global Studies Quarterly* 2 (4). <https://doi.org/10.1093/isagsq/ksac051>.

resolution, it considered what was done as an example of Western selfishness.⁸⁰ Chinese leaders frequently stated that solutions to domestic issues must be “Libyan-led” and “Libyan-owned.”⁸¹ China expressed worry over the destabilization of the area after the intervention, leading to greater extremism and arms distribution in North Africa. The Latin American states were split over Libya. While a few approved of the resolutions, others were deeply concerned about the intervention’s direction. Venezuela was very loud in its criticism; Hugo Chávez warned that the intervention was an act of imperialism, describing it as a “disguise” for foreign control over Libya’s resources and political fate.⁸² He provided an international mediation attempt, which never gained pace, and criticized NATO’s disregard for Libyan sovereignty.

In sum, the Libya intervention reflected a turning point in the Global South’s perception of R2P. Initially, several nations accepted the principle in good faith, acknowledging the need to protect civilians from mass crimes and believing that the international community would fulfill R2P’s restricted humanitarian mission. Despite worries, African governments, Arab countries, and even doubters such as Brazil and India did not oppose Resolution 1973 because they saw R2P as an acceptable tool for tackling crimes against humanity. However, the fast transition from civilian protection to regime change, as reflected by the NATO bombing campaign and Gaddafi’s murder, caused widespread disappointment. This was followed by an abrupt decrease in R2P support in future crises such as Syria and Myanmar, with some Global South nations becoming considerably more hesitant to support any use-of-force conditions, claiming sovereignty, selection, and Western overreach. Libya thus had a negative impact on the Global South’s perception of R2P, shifting it from cautious optimism to profound skepticism, drastically affecting the politics of providing assistance in the future.

Syria (2011-2013)

Overview of the Syrian Crisis, 2011-2012

Alongside Libya, the Syrian crisis began as part of a larger wave of events known as the Arab Spring. What started as peaceful rallies demanding changes to democracy quickly turned violent as President Bashar al-Assad’s administration struck back, killing a total of around 580,000 people to date.⁸³ To suppress opposition, state security forces utilized violent methods like unfair arrests, torture, and mass murders.⁸⁴ These abuses of human rights gained worldwide

⁸⁰ Nuruzzaman, Mohammed. 2022. “‘Responsibility to Protect’ and the BRICS: A Decade after the Intervention in Libya.” *Global Studies Quarterly* 2 (4). <https://doi.org/10.1093/isagsq/ksac051>.

⁸¹ “China Makes Moves to Reopen Economic Ties With Libya, 13 Years After Suspending Trade—Libya Tribune,” July 4, 2024. <https://en.minbarlibya.org/2024/07/04/china-makes-moves-to-reopen-economic-ties-with-libya-13-years-after-suspending-trade/>.

⁸² “Chavez Strikes Out Against US and Israel During Syria Trip—the Classical Music Guide Forums,” August 30, 2006. <https://classicalmusicguide.com/viewtopic.php?p=131443>.

⁸³ “Syrian Civil War | Syrian History | Britannica.” *Encyclopedia Britannica*, July 22, 2025. <https://www.britannica.com/event/Syrian-Civil-War>. ; Global Centre for the Responsibility to Protect. 2025. “Syria.” Global Centre for the Responsibility to Protect. March 14, 2025. <https://www.globalr2p.org/countries/syria/>

⁸⁴ Human Rights Watch. 2011, “‘We’ve Never Seen Such Horror’ | Crimes against Humanity by Syrian Security Forces,” Human Rights Watch. June 2011. <https://www.hrw.org/report/2011/06/01/weve-never-seen-such-horror/crimes-against-humanity-syrian-security-force>

attention, especially when claims of mass massacres came from towns such as Homs and Hama.⁸⁵

However, unlike in Libya, where the international community acted fast under the R2P framework, efforts to intervene in Syria were immediately denied. Several draft UNSC resolutions denouncing the Syrian regime's conduct were rejected by Russia and China.⁸⁶ The Russian representative claimed that the draft resolution left out placing the blame on the armed opposition, while Western and Arab governments accused China and Russia of protecting a dictatorship that commits atrocities against its own people.⁸⁷ The most significant comment from the meeting was, "It is a veto on principle, a refusal of all Council resolutions against Syria." It dismisses the legitimate goals of the Arab Spring. This underlined rising discontent inside the Council, specifically the P3 (the United States, the United Kingdom, and France) and a few Arab states.⁸⁸ The international conflict declined as Syria's unrest continued, and in 2013, Assad's administration broke a "red line" by releasing chemical weapons in Ghouta, killing over 1,400 people.⁸⁹

Global South Attitudes in 2011

After the Libyan intervention in 2011, much of the Global South was cautious about the Syrian situation. Many African and Asian nations that had initially backed or abstained on the Libyan R2P resolution (1973) felt misled by the way NATO carried out the Libya operations, which they saw as shifting from civilian protection to outright regime change.⁹⁰ This mistrust influenced their assessment of any proposed UNSC action on Syria. Brazil, India, and South Africa, all non-permanent Council members at the time, emphasized sovereignty, political solutions, and non-intervention.⁹¹ In particular, Brazil's support for the "Responsibility While Protecting" (RwP) framework in late 2011 reflected an inherent dissatisfaction with how R2P was being implemented.⁹²

Importantly, countries in the Global South often expressed their concerns not as support for Assad, but as fears about Western superiority and double standards. India's representative emphasized the importance of political dialogue between the Syrian government and the

⁸⁵ "Syria - United States Department of State," 2025. United States Department of State, January 3, 2025. <https://www.state.gov/reports/2016-country-reports-on-human-rights-practices/syria>.

⁸⁶ "Russia and China Veto Draft Security Council Resolution on Syria," UN News. October 4, 2011. <https://news.un.org/en/story/2011/10/390412>.

⁸⁷ "Russia and China Veto Draft Security Council Resolution on Syria," UN News. October 4, 2011. <https://news.un.org/en/story/2011/10/390412>.

⁸⁸ United Nations Security Council, S/PV.6627 (2011), October 4, 2011, <https://docs.un.org/en/S/PV.6627>.

⁸⁹ Ben, Hubbard, 2018. "Dozens Suffocate in Syria as Government Is Accused of Chemical Attack." The New York Times, April 8, 2018. <https://www.nytimes.com/2018/04/08/world/middleeast/syria-chemical-attack-ghouta.html>.

⁹⁰ Christopher, Zambakari, Christopher. 2016. "The Misguided and Mismanaged Intervention in Libya: Consequences for Peace." African Security Review 25 (1): 44–62. <https://doi.org/10.1080/10246029.2015.1124795>.

⁹¹ Cruz Aguilar. 2024. "Leveraging Influence on the UN Security Council: The Cases of Brazil, India, and South Africa." Dados 68 (1). <https://doi.org/10.1590/dados.2025.68.1.354>.

⁹² Serbin, Andrés, and Andrei Serbin Pont. 2015. "Brazil's Responsibility While Protecting: A Failed Attempt of Global South Norm Innovation?" February 2, 2015. https://www.researchgate.net/publication/281438900_Brazils_Responsibility_while_Protecting_a_failed_attempt_of_Global_South_norm_innovation

opposition without preconditions, while South Africa repeatedly recommended neutrality and cautioned against using R2P as a ploy for forced regime change.⁹³ Their attitudes reflected not just geopolitics but also a postcolonial distrust of Western-led operations. At the same time, they faced growing criticism for being accomplices in silence. The veto in S/PV.6627 in October 2011 angered many Western and Arab delegations, and an increasing number of democratic voices accused the Global South of prioritizing sovereignty over human life.⁹⁴

Global South Attitudes After 2013

As the Syrian war continued into 2013, distinguished by increasing violence and repeated violations of international law, beliefs in Global South nations began to shift, although hesitantly. The chemical weapons assault in Ghouta in August 2013 was a turning point.⁹⁵ While direct military involvement remained out of the question because of the Russian opposition, the UN Security Council reached a rare consensus and passed Resolution 2118, which demanded the elimination of Syria's chemical weapons inventory.⁹⁶ During the Security Council meeting S/PV.7038 in September 2013, all participants condemned the use of chemical weapons, and the resolution was unanimously accepted.⁹⁷ Pakistan stated, "The resolution was a landmark text, which demonstrated the Security Council's leadership. Its unanimous adoption meant the international community had taken ownership of the process of eliminating Syria's chemical weapons program."⁹⁸ This was a unique moment of agreement in which R2P rhetoric was embraced without resulting in direct military engagement.

As the conflict progressed and new atrocities—including hospital attacks, starvation sieges, and additional chemical incidents—came out, even countries previously skeptical of intervention began to support more concrete international measures such as sanctions, accountability mechanisms, and Syria's referral to the International Criminal Court (ICC).⁹⁹ By the middle of the 2010s, several Global South nations, including Nigeria, Chile, and Malaysia, had supported resolutions promoting humanitarian access and accountability, such as Resolution

⁹³ "India Favours Political Dialogue in Syria." 2012. The Hindu. February 2012.

<https://www.thehindu.com/news/international/india-favours-political-dialogue-in-syria/article2850070.ece%20> ; Halliyade, Muditha. 2016. "Indiana Journal of Law and Social Equality Syria -Another Drawback for R2P?: An Analysis of R2P' S Failure to Change International Law on Humanitarian Intervention." Indiana Journal of Law & Social Equality 4 (2). <https://www.repository.law.indiana.edu/cgi/viewcontent.cgi?article=1049&context=ijlse>.

⁹⁴ "S/PV.6627 : UN Documents: Security Council Report," n.d. www.securitycouncilreport.org, <https://www.securitycouncilreport.org/un-documents/document/golan-heights-s-pv-6627.php>.

⁹⁵ Elisabeth Baer, "The Threat of Inaction in Response to Violations of International Law: A Syrian Case Study." Small Wars Journal by Arizona State University, April 28, 2025. <https://smallwarsjournal.com/2025/04/28/the-threat-of-inaction-in-response-to/>.

⁹⁶ "Security Council Requires Scheduled Destruction of Syria's Chemical Weapons, Unanimously Adopting Resolution 2118 (2013) | Meetings Coverage and Press Releases," September 27, 2013. <https://press.un.org/en/2013/sc11135.doc.htm>

⁹⁷ United Nations Security Council, S/RES/2118 (2013), September 27, 2013, [https://undocs.org/S/RES/2118\(2013\)](https://undocs.org/S/RES/2118(2013)).

⁹⁸ "Security Council Requires Scheduled Destruction of Syria's Chemical Weapons, Unanimously Adopting Resolution 2118 (2013) | Meetings Coverage and Press Releases," September 27, 2013. <https://press.un.org/en/2013/sc11135.doc.htm>.

⁹⁹ Syrian Network for Human Rights. 2024. "Summary of the Assad Regime's Crimes against the Syrian People over the Last 14 Years | Syrian Network for Human Rights." Snhr.org. December 20, 2024. <https://snhr.org/blog/2024/12/20/summary-of-the-assad-regimes-crimes-against-the-syrian-people-over-the-last-14-years/>.

1325, Resolution 1960 and Resolution 2122, each creating frameworks for protecting women.¹⁰⁰ Despite this, every strong resolution was met with vetoes from Russia and China, perpetuating the idea that the fate of Syrian people was determined by UNSC politics rather than morality.¹⁰¹

The tone of Global South statements in later sessions changed even more drastically. For example, by 2015, even previously reluctant governments such as Brazil began emphasizing justice, documenting war crimes, and the need for international action, although under the framework of the United Nations, stating, “We welcome the unanimous adoption of resolution 2254 (2015) on Syria. ... No effort should be spared to move forward a Syrian-led political process based on full respect for human rights and the independence, sovereignty, unity and territorial integrity of Syria.” Turkey agreed, stating “The status quo cannot continue... To alleviate the suffering of Syrian civilians, more resources must be allocated to UN humanitarian deliveries in the country.”¹⁰² Social organizations in the Global South had also begun to take more powerful stances, such as the Global Civil Society, which included 47 groups that issued a public call for the UNSC to restrain the use of vetoes and swift action.¹⁰³

By this point, dissatisfaction had escalated among the international community at the inaction in Syria. Many states began to see the R2P norm as fundamentally meaningless when permanent members’ vetoes made collective action impossible. Syria revealed that, while the moral agreement on mass atrocity prevention was expanding, the institution to implement it remained dysfunctional. By 2015, some Global South countries had started backing the basic ideas behind R2P again, even after the fallout from Libya. They saw the need to stop atrocities like those happening in Syria and supported the principle of protecting civilians. However, inside the UN Security Council, big-power rivalries and veto politics had become worse than ever. This made it nearly impossible for the Council to agree on any real action, even when most countries wanted it.

The inaction in the Syrian crisis was ultimately driven by the Global South’s distrust of R2P as an evolving, reliable norm. While many Global South states examined Syria with reservations following the fallout from Libya, fearing another Western-led regime change disguised as humanitarian intervention, their positions were not based on support for Assad but rather on concerns about sovereignty, fairness, and double standards in international law. However, as the conflict escalated and atrocities increased, particularly following the 2013 chemical weapons attacks, a subtle shift occurred: countries that had previously been hesitant to

¹⁰⁰ “Security Council Unanimously Adopts Resolution 2242 (2015) to Improve Implementation of Landmark Text on Women, Peace, Security Agenda | Meetings Coverage and Press Releases,” October 13, 2015. <https://press.un.org/en/2015/sc12076.doc.htm>.

¹⁰¹ UN News. “Russia and China Veto Draft Security Council Resolution on Syria,” October 4, 2011. <https://news.un.org/en/story/2011/10/390412>

¹⁰² “Syria Facing Highest Levels of Humanitarian Need Since Start of 13-Year Crisis”, Senior Official Tells Security Council | Meetings Coverage and Press Releases, June 25, 2024. <https://press.un.org/en/2024/sc15744.doc.htm> .

¹⁰³ “Working Methods Notes | Security Council,” n.d. <https://main.un.org/securitycouncil/en/content/working-methods-notes>.

support any strong measures began to support non-military forms of intervention such as accountability efforts, humanitarian access, and documentation of war crimes.¹⁰⁴

The Syrian crisis demonstrated that, even while there was growing consensus on the need to prevent atrocity crimes, the tools for intervention were obstructed by great power geopolitics. As a result, many in the Global South saw R2P as an acceptable idea that was undermined by selective implementation, systemic inequalities, and the P5's continued control over global justice. Syria did more than just highlight the fragility of R2P; it reinforced the Global South's perception that without changes in institutions, the norm will continue to be enforced inconsistently, favoring those in power over the vulnerable. At first, many Global South countries quickly dismissed using R2P in Syria, seeing it as another excuse for Western intervention after Libya. They worried it would lead to regime change and violate Syria's sovereignty. Over time, however, as the war dragged on and atrocities grew, some began to see value in R2P's core idea of protecting civilians. This led to a slow, cautious acceptance, but only if it was done collaboratively with the government and without abuse.

Myanmar (2017-2018)

Overview of the Rohingya Crisis, 2017

The Rohingya crisis began in August 2017, when Myanmar's military, known as the Tatmadaw, initiated a fatal operation in Rakhine State, reportedly in retaliation to attacks by the Arakan Rohingya Salvation Army (ARSA).¹⁰⁵ Over 600,000 Rohingya citizens fled across the border into Bangladesh in weeks, resulting in a "humanitarian catastrophe," as described in the UN Security Council Report.¹⁰⁶ At the Security Council meeting S/PV.8060 on September 28, 2017, the Secretary-General warned of a serious deterioration in Rakhine, with rising refugee numbers and increasing civilian suffering.¹⁰⁷ The meeting highlighted the pressing nature of the issue, which has been increasing since the ARSA assaults on August 25. The Rohingya situation reached concerning levels, with UN High Commissioner Zeid Ra'ad Al Hussein describing the crackdown as ethnic cleansing or genocide.¹⁰⁸

However, despite the seriousness of the crimes, the Security Council failed to approve a binding resolution due to China and Russia's concerns about sovereignty and non-interference. In that session, the Myanmar government argued that the claims of ethnic cleansing were "malicious and unsubstantiated chatter" and denied that any cleansing operations had taken place after early September, while national security officials called the allegations of genocide

¹⁰⁴"Syria's Chemical Weapons Declaration Still Inaccurate, Unfinished, Top Disarmament Official Tells Security Council, Reiterating Need for Damascus to Fully Cooperate | Meetings Coverage and Press Releases," July 11, 2023. <https://press.un.org/en/2023/sc15350.doc.htm>.

¹⁰⁵ UNHCR. 2024. "Rohingya Refugee Crisis Explained." [Www.unrefugees.org](https://www.unrefugees.org/news/rohingya-refugee-crisis-explained/). 2024. <https://www.unrefugees.org/news/rohingya-refugee-crisis-explained/>.

¹⁰⁶United Nations Security Council. "The Situation in Myanmar." United Nations Security Council Report. Vol. 18–12959, 2017. https://main.un.org/securitycouncil/sites/default/files/part_i_2016-2017_myanmar.pdf.

¹⁰⁷United Nations Security Council, S/PV.8060 (2017), November 16, 2017, <https://docs.un.org/en/S/PV.8060>.

¹⁰⁸ "UN: Myanmar Should Be Investigated for Crimes Against Rohingya." Al Jazeera, March 9, 2018. <https://www.aljazeera.com/news/2018/3/9/un-myanmar-should-be-investigated-for-crimes-against-rohingya>.

defamatory.¹⁰⁹ Meanwhile, Bangladesh warned of a further 20,000 Rohingya entering on the same day and urged a UN-mandated “safe zone” to protect surviving civilians.¹¹⁰ Other Council members, including those from the United Kingdom, France, Egypt, the United Arab Emirates, Uruguay, Ethiopia, Senegal, and Sweden, criticized a pattern of ethnic cleansing and crimes against humanity, holding Myanmar’s government solely responsible for civilian protection.¹¹¹

Regional Responses to the Rohingya crisis

The regional reaction to the Rohingya issue, especially from the Association of Southeast Asian Nations (ASEAN), was defined by extreme caution, strategic vagueness, and a firm dedication to the principle of non-interference. Since its creation in 1967, ASEAN has prioritized internal stability, mutual respect for sovereignty, and consensus-based decision-making above diplomatic coercion or harsh sanctions against member countries.¹¹² This political culture strongly influenced how the organization responded to Myanmar’s military-led ethnic cleansing attack against the Rohingya. Even as satellite photographs and victim testimonials showed deliberate mass atrocities, burned towns, gang rapes, and mass graves, ASEAN’s collective voice was noticeably silent. Within ASEAN, member nations such as Thailand, Cambodia, Laos, and Vietnam continuously advocated for a diplomatic, non-confrontational strategy, fearing that a precedent would be created against them in future crises.¹¹³ This was motivated not only by concern for Myanmar but also by a desire to avoid foreign involvement in domestic matters and a common authoritarian attitude. The ASEAN Charter, particularly Articles 2 and 7, outlines this rule of non-intervention, giving even one disagreeing member state the power to weaken or prevent collective action.¹¹⁴

During the peak of the Rohingya crisis in 2016-2017, this severely undermined the bloc’s ability to act forcefully. ASEAN’s reaction shows not just institutional weakness but also a deeper ideological belief in the sovereignty-first concept of regionalism. The Rohingya tragedy was not the first time ASEAN neglected to take strong action on domestic human rights violations. However, Myanmar’s situation was especially grave since the killings occurred in real time, and ASEAN’s silence essentially allowed the military’s lawlessness. By 2021, following

¹⁰⁹ “Amid ‘Humanitarian and Human Rights Nightmare’ in Myanmar, Secretary-General Urges Full Access for Aid, Safe Return of Displaced Rohingya, End to Military Operations | Meetings Coverage and Press Releases,” September 28, 2017. <https://press.un.org/en/2017/sc13012.doc.htm>.

¹¹⁰ International Crisis Group. 2023. “Bangladesh/Myanmar: The Dangers of a Rohingya Insurgency.” Asia Report No. 348. Brussels: International Crisis Group, December 14, 2023. <https://www.crisisgroup.org/asia/south-east-asia/myanmar-bangladesh/348-bangladeshmyanmar-dangers-rohingya-insurgency>.

¹¹¹ “Council Condemns Alleged Systematic and Gross Violations of Human Rights against Rohingya Muslims and Other Minorities in Myanmar.” n.d. OHCHR. <https://www.ohchr.org/en/press-releases/2017/12/council-condemns-alleged-systematic-and-gross-violations-human-rights>.

¹¹² ASEAN. 2020. “What We Do.” Association of Southeast Asian Nations. 2020. <https://asean.org/what-we-do/>.

¹¹³ Jones, Lee. (2012). ASEAN, Sovereignty and Intervention in Southeast Asia. *CONTEMPORARY SOUTHEAST ASIA*. 34. 303. 10.1355/cs34-2i

¹¹⁴ Association of Southeast Asian Nations. “THE CHARTER ASEAN.” Print, Book. ASEAN Secretariat, January 2008. <https://asean.org/wp-content/uploads/images/archive/publications/ASEAN-Charter.pdf>.

the military takeover, ASEAN had been forced to recognize its limits and adopted the “Five-Point Consensus” on Myanmar.¹¹⁵

Global South Responses to the Rohingya Crisis

In contrast, the international response from Global South nations to the Rohingya issue was significantly more complicated and diverse than regional ASEAN reactions, and it changed dramatically between 2016 and the post-2017 period. Initially, several Global South governments took cautious or unclear stances, mirroring ASEAN’s commitment to sovereignty and non-interference. Countries with significant geopolitical or economic links to Myanmar, such as India, China, and Russia, have defended the situation as a local problem and resisted any sort of international action, including condemnations by the United Nations Security Council. India, for example, maintained a mixed stance: while sending humanitarian aid to Bangladesh and supporting refugee return, it also stressed Myanmar’s “territorial integrity” and refused to recognize the Rohingya as refugees.¹¹⁶

However, this cautious position was not shared throughout the Global South. Other nations, particularly those in Africa, Latin America, and the Middle East, showed a considerably stronger willingness to deal with the crisis through a lens of international accountability, including R2P. Egypt, a non-permanent UNSC member at the time, strongly supported humanitarian access and demanded serious investigations, stating, “What choice are we leaving to these people, other than taking up arms to defend themselves?”¹¹⁷ Uruguay, representing Latin America, was much more outspoken. In the same UNSC meeting, Uruguay’s ambassador emphasized that reports of rape, mass murder, and forced displacement constituted “crimes against humanity” and that “those responsible must be held accountable.”¹¹⁸ These stances were not just solely discourse; they laid the foundation for institutional action.

The Global South’s attitude to the Rohingya issue reveals both variation and development. While some governments committed to sovereignty guidelines, others took a more human rights-oriented approach. This conflict mirrors a larger discussion in the Global South about what R2P could mean in reality. For many, Libya’s aftermath was an important lesson of overreaction. However, Myanmar provided a new scenario: one in which no action, whether diplomatic or legal, would be morally unjustified. While the Global South failed to act in unison,

¹¹⁵ Ali, Faisal. 2022. “The Responsibility to Protect and the International Refugee Regime: A Comparative Analysis of the Rohingya and Syrian Refugee Crises.” *UNISCI Journal* 59: 35-60.
<https://www.unisci.es/wp-content/uploads/2022/11/UNISCIDP59-3ALI.pdf>.

¹¹⁶ Taufiq, Hossain Ahmed. 2019. “China, India, and Myanmar: Playing Rohingya Roulette?” *Global Political Transitions*, 81–99. https://doi.org/10.1007/978-981-13-7240-7_4.

¹¹⁷ “We Must Go Above, Beyond Compliance, Fully Protect Civilians Against ‘Harms They Are Suffering on Our Watch’, Senior Humanitarian Official Tells Security Council | Meetings Coverage and Press Releases,” May 21, 2024. <https://press.un.org/en/2024/sc15702.doc.htm>.

¹¹⁸ Jun, Zhang. “Letter Dated 27 May 2021 From the President of the Security Council Addressed to the Secretary-General and the Permanent Representatives of the Members of the Security Council.” United Nations, May 27, 2021.
https://www.securitycouncilreport.org/atf/cf/%7B65BF9B-6D27-4E9C-8CD3-CF6E4FF96FF9%7D/s_2021_505.pdf.

many of its members began to reinterpret what unity entails: one that involves justice, humanity, and shared responsibility, even if sovereignty remains an essential concept.

The international reaction to the Rohingya issue in Myanmar shows a significant shift in the Global South's perspective of the Responsibility to Protect (R2P), particularly in comparison to the backlash following the 2011 Libya intervention. The Myanmar case, which occurred just a few years after Libya, showed that, while many Global South nations remained cautious of military intervention and strongly valued sovereignty, there was a growing openness to non-military applications of R2P, particularly those centered on investigations, humanitarian aid, and legal accountability. The Tatmadaw's misconduct was so grave and well-documented that many nations found it impossible to remain silent. As a result, Myanmar saw a greater acceptance of R2P's non-coercive measures, such as requests for ICC referrals and support for fact-finding missions. This emphasized a small but significant shift: rather than rejecting R2P outright, many Global South governments attempted to recover and reinterpret it in ways that stressed justice and cooperation while avoiding the abuses seen in Libya. While divides remained, the Myanmar crisis symbolized a period of careful renewed interest with R2P, implying that, under the appropriate conditions, the norm might still function as an instrument for international unity and protection without being inherently linked to Western military intervention.

CONCLUSION

This paper examined the question: how did non-Western UN member states' attitudes of the Responsibility to Protect (R2P) policy change after the 2011 Libya intervention? The goal was to determine if Libya led to a universal rejection of R2P across the Global South or if it created more nuanced, regionally specific adjustments to the norm. I argued that Libya did not result in a general rejection of R2P, instead it increased skepticism in certain nations while assisting progressive approaches in others. Clear changes developed throughout all four cases studies: Sudan (2006), Libya (2011), Syria (2011-2012), and Myanmar (2017-2018). Sudan reflected the Global South's hesitant acceptance of R2P, which was based on sovereignty and regional control, but Libya confirmed long-held concerns that R2P may be used for regime change. This triggered a more cautious stance in following crises, like in Syria, where fear resulted in a lack of progress despite substantial crimes. Myanmar, on the other hand, demonstrated a cautious renewed interest with non-military aspects of R2P, particularly legal accountability and humanitarian access, suggesting that the norm had value when separated from aggressive military intervention.

The data from UN Security Council discussions, vote trends, and diplomatic remarks supports these conclusions. Sudan's emphasis on "African solutions," Libya's rejection of the AU roadmap, Syrian intervention's continuous vetoes, and Myanmar's campaigns for an ICC referral all highlight that the Global South's R2P stance evolved from cautious optimism to deep skepticism and eventually selective resurgence. These findings fill a gap in previous scholarship, which frequently depicts the Global South as an identical bloc that rejects R2P outright following

Libya, ignoring regional and ideological differences. By showing this variation, my research helps to provide a deeper understanding of Global South attitudes on R2P. It shows that these governments are not spectators or obstructors of international norms but rather cautious and sovereignty-focused, trying to balance atrocity prevention with sovereignty and cultural nuance.

The implications of these findings extend to the present. In an era of increased geopolitical tension and mass atrocity risks, such as Gaza and Sudan's continuous civil war, the credibility of R2P depends on closing the security disconnect highlighted by Libya. Recognizing the Global South's diverse perspectives is critical for developing valid and successful solutions. If the international community can modify R2P to stress accountability, proportionality, and inclusive decision-making, the theory may still function as a uniting moral and political framework rather than a cause of contention. Recognizing the Global South's diverse perspectives is critical for developing valid and successful solutions. This requires a fundamental shift from power politics to a rules-based consensus. Operational guidelines must be established to ensure military interventions are a last resort and strictly limited to their humanitarian mandate. Ultimately, the doctrine's legitimacy hinges on its consistent and impartial application. If the international community can modify R2P to stress accountability, proportionality, and inclusive decision-making, the theory may still function as a uniting moral and political framework rather than a cause of contention.

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Role of Silence in Harry Potter Films By Aryan Agarwal

Abstract

This paper examines the role of silence as a recurring narrative and emotional device in the *Harry Potter* film series. While scholarship on the franchise has largely focused on its iconic musical motifs, particularly John Williams' "Hedwig's Theme," this study argues that silence itself functions as a motif, shaping audience perception with equal force. Across the series, silence is not simply the absence of music but a deliberate sonic choice that conveys fear, grief, secrecy, and transformation. Through close analysis of key scenes—including Voldemort's resurrection in *Goblet of Fire*, Sirius Black's death in *Order of the Phoenix*, and Snape's memory sequence in *Deathly Hallows Part 2*—this paper demonstrates how silence operates differently depending on context: as a marker of power and dread in Voldemort's case, or as an expression of grief and ambiguity in Snape's. More broadly, silence amplifies abstract themes such as loss, isolation, and the fragility of humanity. Tracing the films' evolution under four composers, the study shows how silence grows more frequent and layered as the narrative darkens, complementing shifts in tone and character development. Ultimately, silence functions as a structural and thematic counterpart to music: where music provides continuity, silence punctuates rupture. By treating silence as a motif, this paper broadens the scope of film music analysis, highlighting how the interplay of sound and absence deepens cinematic storytelling and enhances audience engagement in the *Harry Potter* films.

Introduction

The music of the *Harry Potter* film series plays a vital role in shaping the emotional tone and guiding the audience's engagement with the story. One of the most significant musical techniques used throughout the films is the musical motif—a short, recurring musical idea associated with a particular character, object, emotion, or theme. While the specific term "leitmotif" is most closely associated with the work of Richard Wagner, the idea of using recurring musical themes to represent characters, ideas, or emotions dates back much earlier in musical history. Wagner helped formalize and popularize the technique in opera, making these motifs more structurally and dramatically central. In film, musical themes function as signposts that help the audience recognize narrative developments, emotional shifts, or character transformations without the need for dialogue (William 181). These motifs can evolve across a film or series to reflect changes in the story, deepening their emotional or symbolic meaning over time.

In *Harry Potter*, musical themes are central to the cohesion and emotional depth of the series. The most iconic example is John Williams' "Hedwig's Theme," a sweeping, celesta-driven melody first introduced in *The Philosopher's Stone*. While originally linked to Harry's owl, the theme quickly becomes emblematic of the entire magical world and is reprised throughout all eight films, often in transformed variations that reflect shifts in tone, mood, and narrative stakes. This adaptability is a hallmark of effective motif writing—it allows a single

musical idea to gain variety while remaining recognizable. Another example is the poignant motif tied to Lily Potter's love for Harry, which reappears during emotionally charged scenes, especially when Harry confronts the loss of his parents. These musical themes act as emotional anchors, helping viewers grasp connections between moments across different parts of the saga.

The progression of musical tone and directors across the *Harry Potter* series closely aligns with the characters' psychological development and the increasingly serious themes of the narrative. The first three films, scored by John Williams, are characterized by whimsical, richly orchestrated themes that reflect the wonder and discovery of the magical world. Yet even within Williams' contributions, there is a noticeable tonal shift from *Chamber of Secrets* to *Prisoner of Azkaban*, which coincides with the arrival of a new director, Alfonso Cuarón. As the series progressed, new composers—Patrick Doyle (*Goblet of Fire*), Nicholas Hooper (*Order of the Phoenix*, *Half-Blood Prince*), and Alexandre Desplat (*Deathly Hallows* Parts 1 and 2)—each brought their own stylistic interpretations. Doyle introduced a more tragic and romantic tone that matched the film's shift toward adolescence and loss. Hooper's work leaned into introspection and psychological tension, while Desplat's scores are notably sparse and atmospheric, reflecting the war-torn world and emotional exhaustion of the final installments. Though these changes seem to correspond with the increasingly dark narrative, it is difficult to determine whether the music evolved primarily due to the story itself, changes in directorial vision, or the stylistic choices of individual composers.

While music often serves as the emotional and narrative backbone of a film, silence can be just as powerful—and sometimes even more so. In cinematic storytelling, silence is never truly empty; it is a deliberate choice that can convey mood, signal narrative tension, or draw attention to visual detail and character emotion. (Donaldson et al. *When Film Breathes: Topographies of Silence and Not-Quite-Sound*, 2023). Directors and composers frequently use silence to heighten realism, underscore psychological depth, or provide contrast to a heavily scored moment. For instance, a sudden drop in sound can create suspense in a thriller, amplify the intimacy of a character's quiet revelation, or make an explosion feel more jarring when it finally arrives. Crucially, the strategic use of silence can enhance immersion by encouraging viewers to engage more deeply with the image and subtext rather than relying on musical cues to direct their interpretation.

In this way, silence becomes a kind of negative space—not merely the absence of sound, but a presence with its own meaning and rhythm. It can indicate isolation, emotional numbness, the supernatural. Films like *No Country for Old Men* or *The Revenant* and directors such as David Fincher demonstrate how the omission of music in key scenes can elevate tension or realism, forcing the audience to rely on ambient sound or the characters' breath, footsteps, or silence itself to understand what's at stake (Lim, *The New York Times*, 2008). Even in more traditional scores, brief silences can make the return of music feel more impactful. Thus, silence operates not only as a break from music but as a deliberate narrative and emotional tool in its own right.

In the *Harry Potter* films, silence is used not merely as an absence of music but often functions as a recurring element that contributes to the emotional and thematic atmosphere of key scenes. Across the series, moments of grief, fear, revelation, and power are frequently accompanied by stretches of silence, suggesting a deliberate effort to highlight their narrative significance. For example, after Cedric Diggory's death in *Goblet of Fire*, the absence of music draws attention to the gravity of the moment and may be intended to reflect the shift from magical competition to real-world violence. Similarly, in *Order of the Phoenix*, when Harry reacts to Sirius's death, the lack of a musical score allows viewers to focus on the emotional weight of the scene. In *Deathly Hallows Part 1*, the silence during the animated "Tale of the Three Brothers" sequence lends the tale a timeless or mythic quality. While we cannot know the exact intentions behind these choices, the recurring use of silence in such pivotal scenes invites interpretation and suggests that it plays a meaningful, if subtle, role in the films' emotional storytelling.

This recurring use of silence across the series suggests that it acts as a kind of sonic element—one that signals transformation and emotional intensity. Rather than disrupting the viewer's experience, these moments of silence enhance it, forcing audiences to pay closer attention to visual cues, character expressions, and thematics. Silence, in this sense, functions as a distinct musical motif: a tool of storytelling with the power to provoke viewers' reflection, elevate tension, and emphasize loss or change. Discerning the role of silence as a discrete phenomenon functioning within the musical structures in the films is the object of my investigation. **In particular, how does silence function as a musical motif in the *Harry Potter* film series, and in what ways does it shape the viewer's emotional and narrative experience?**

Analysis and Discussion

To understand how silence operates meaningfully across the *Harry Potter* films, it's necessary to examine not just when silence is used, but what it represents. Certain characters and themes are particularly tied to silence in ways that go beyond simple atmosphere. Voldemort and Snape, for example, are often accompanied by moments of restrained sound or complete quiet, and these choices reflect and deepen their narrative roles. Voldemort's connection to silence seems especially tied to fear, control, and death—concepts that define his character and the atmosphere around him. Snape's silence, on the other hand, appears more emotionally ambiguous, maybe suggesting secrecy, isolation, and hidden grief. More broadly, silence in the series frequently represents abstract ideas like fear and a lack of humanity, especially in scenes where music is deliberately withheld to emphasize tension, loss, or emotional detachment. These uses of silence are not random but consistent and evolving, making it a recurring expressive tool that parallels traditional musical scoring. In the following paragraphs, I will examine these characters and themes individually to explore how silence functions as an element across the series.

Voldemort is perhaps the character most frequently associated with silence, and the absence of music in his scenes is often more striking than the presence of any sound. Throughout

the series, encounters with him—or even the mention of his name—are marked by hesitation, stillness, and tension, all of which are often mirrored by sonic restraint. One of the most effective uses of silence occurs in *Goblet of Fire*, during the graveyard scene where Voldemort regains his body. As the resurrection begins, the score drops out entirely, replaced by eerie ambient sound and pauses that let the viewer sit in the horror of the moment. (Harry Potter and the Goblet of Fire) This silence emphasizes how unnatural and terrifying the ritual is—it suspends time and pulls focus onto the physical transformation and Harry’s fear. Similarly, in *Deathly Hallows Part 2*, the silence that precedes Harry’s walk into the Forbidden Forest creates an overwhelming sense of dread. (Harry Potter and the Deathly Hallows: Part 2). The absence of sound marks the gravity of the situation and the looming presence of Voldemort as the ultimate threat. These quiet moments aren’t used randomly; they function to amplify Voldemort’s dominance, fear, and the finality he represents. Silence becomes a sign of control—his presence silences the world around him.

While Voldemort’s silence is terrifying and dominating, Snape’s is more emotionally layered. His character is defined by restraint—both emotionally and verbally—and this is mirrored in the films’ use of quiet in scenes that center on him. In contrast to loud or dramatic musical cues, the quietness in Snape’s scenes often reflects ambiguity, sadness, and internal conflict. In *Half-Blood Prince*, for example, the moments after Dumbledore’s death are largely silent, especially when Snape flees the castle. (Harry Potter and the Half Blood Prince). The lack of a score allows viewers to focus entirely on facial expressions and the silence between characters, emphasizing the betrayal without melodrama. Even more powerful is the ‘Pensieve’ scene in *Deathly Hallows Part 2*, which reveals Snape’s memories. Here, silence appears again, not to heighten fear, but to slow the pacing, letting the audience absorb the emotional weight of each revealed memory. (Harry Potter and the Deathly Hallows: Part 2). There are soft ambient textures, but the absence of sweeping music lets us engage with Snape’s grief, guilt, and long-held secrets without manipulation. This form of silence allows the viewer to reflect instead of react. Snape’s silence, then, is less about power and more about emotional concealment. I argue that it suggests he is deeply misunderstood—and that, beneath his cold exterior, he is profoundly human.

Beyond character-specific examples, silence is also used to express broader, more abstract themes throughout the series, especially fear and a lack of humanity. These themes often appear in scenes where hope is absent, or where death and emotional numbness take over. In *Order of the Phoenix*, the Ministry battle sequence has several moments where all sound cuts out after Sirius’s death. (Harry Potter and the Order of the Phoenix). The quiet here isolates Harry’s reaction and emphasizes his emotional turmoil—it makes the audience experience his shock physically through the soundscape. In *Deathly Hallows Part 1*, the animated sequence of “The Tale of the Three Brothers” uses silence between the narration and sparse scoring to give the myth a timeless, eerie quality. The lack of musical warmth reflects the inevitability of death and the coldness of the characters’ fates. Silence is also used when characters are subjected to cruelty or emotional disconnection, such as when the trio visits Godric’s Hollow or when Harry watches

Snape's death in *Part 2*. In all these scenes, silence highlights the absence of empathy or safety. It becomes a way of expressing what is too painful or unnatural to put into music, helping represent emotional chasms or moral dilemmas.

As the *Harry Potter* films progress and the tone grows darker, the use of silence becomes more frequent and more layered. In the early films, under John Williams' direction, silence is used sparingly—most scenes are supported by a full, magical score that reflects the wonder of discovering a new world. But by *Order of the Phoenix* and onward, silence becomes more central to emotional storytelling. Nicholas Hooper and Alexandre Desplat, in particular, use silence not just as a break from music, but as a narrative device. Their scores are often quieter in general, and they make room for silence in ways that earlier films did not. This shift aligns with the characters' maturation and the darker, more psychological focus of the later storylines. Even the battle scenes in *Deathly Hallows Part 2* contain stretches of quiet, such as the walk through the ruined Hogwarts courtyard or the forest scene before Harry's sacrifice. These silences don't just fill space—they reflect the cost of war or the weight of death.

Some may argue that not all silence in the *Harry Potter* films is meaningful—that sometimes, silence is just a practical break in the sound design, or a result of pacing choices unrelated to symbolism. It's also fair to point out that not every quiet moment carries deep thematic weight. Indeed, not all silence in the films can be assigned a symbolic function, but rather that its repeated and purposeful use in emotionally significant scenes allows it to function as a meaningful motif. Others may argue that since film sound design is always intentional, silence does not deserve special focus. Yet music in *Harry Potter* has already been widely analyzed for how it represents characters and themes. Silence, on the other hand, has not received the same attention, despite being used just as deliberately. What makes *Harry Potter* a unique case is the fact that the series spans over a decade, with multiple directors and composers, yet the symbolic power of silence remains consistent, even as its application evolves. This makes it a particular example of continuity in sonic storytelling—an element that links all eight films despite changes in personnel, tone, and cinematic style. Silence, then, deserves closer attention not just as an absence, but as a narrative force in its own right.

Conclusion

This paper's argument helps us better understand the viewer's experience by clarifying how silence shapes interpretation and emotional response. When silence recurs at pivotal points in the *Harry Potter* films, it does more than break from music; it becomes a recognizable marker of grief, tension, or confrontation. For the viewer, this repetition creates expectation and recognition, similar to how traditional motifs function. Silence draws the audience's attention inward, asking them to confront the raw emotion or the unsettling gravity of a scene without the guidance of melody. In this way, silence heightens the intensity of the viewer's experience by demanding reflection from the viewer.

If silence signifies these moments of rupture—loss, fear, or suspension—then music in turn becomes the medium of continuity. Music weaves emotional cohesion across the series,

allowing themes to resurface and transform alongside characters and plotlines. Where silence marks breaks, music provides flow; where silence confronts the viewer with absence, music reassures by returning familiar patterns. Together, music and silence form a contention: one speaks by withholding, the other by repeating. For the audience, this interplay deepens the experience of narrative development. Music helps them connect the dots, while silence makes them pause and absorb the weight of what they may see.

Thus, silence and music are not opposites but partners in storytelling. By treating silence as a motif, we can see how it shapes the rhythm of cinematic experience just as powerfully as orchestral scoring. The recurring presence of silence across the *Harry Potter* series demonstrates that motifs need not be limited to sound. They can also reside in its absence. Ultimately, this paper has argued that silence itself functions as a motif in the films, shaping meaning and emotion across an evolving narrative world.

The significance of this analysis lies in how it broadens the scope of film music studies. Silence has long been recognized as meaningful in cinema, but its treatment as a motif—recurrent, recognizable, and with narrative weight—offers a new way of approaching both film sound and audience reception. Over the history of cinema, silence has evolved from a practical limitation of early sound technology into a deliberate artistic choice, often used to heighten realism, suspense, or introspection. The *Harry Potter* series exemplifies this evolution: by spanning a decade of filmmaking, it provides an unusually consistent framework for studying how silence functions across different directors and composers while maintaining a single, continuous fictional world.

This continuity allows us to see how silence remains effective despite changes in musical style, cinematic tone, and narrative complexity. The films show that silence, strategically deployed with music, enhances contrast and emphasizes meaning. For film composition more broadly, this reveals an important principle: the interplay between music and silence can be as crucial to narrative effect as melody or instrumentation. For the viewer, this interplay shapes how they process the story—when to be guided, when to be left to confront a scene with their own thoughts, and when to recognize repetition of the motif across the narrative of a series.

Ultimately, analyzing silence in this way underscores its centrality to cinema. It is not an absence to be overlooked but an effective and versatile tool for storytelling. In the case of *Harry Potter*, silence operates as a motif that structures audience experience, enriches narrative depth and signals moments of transformation or loss. By drawing attention to what is left unsaid or unscored, it ensures that even in a film world filled with sound and spectacle, absence itself can speak with equal power.

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Leveraging Explainable Machine Learning for Used Car Price Prediction in Turkey's 2025 Market By Kerem Unal

Abstract

This study investigates the prediction of second-hand car prices in Turkey's 2025 market using machine learning techniques. A dataset of 6,675 vehicle listings was analyzed through Linear Regression, Random Forest, and XGBoost models. After hyperparameter tuning, XGBoost achieved the average accuracy with a bootstrapped test R^2 of 0.917, outperforming both Random Forest and Linear Regression. SHAP analysis revealed that year, mileage, engine power, and transmission type were the most important determinants of price, in line with prior literature and market expectations. Compared with earlier regression-based studies, the ensemble models delivered improved accuracy and interpretability. The findings not only provide practical tools for buyers and sellers but also contribute to the academic literature on car price prediction.

Keywords car price, car specifications, region, Turkey, used car, market, machine learning, feature importance analysis, shap

Introduction

Knowing the price of a car before buying or selling it helps both parties to avoid potential losses. One reason why car dealerships are able to make a profit on second-hand cars is that sellers accept less than the car is worth, while buyers pay more than it is worth. To avoid this, buyers and sellers can use machine learning models to predict the price of a used car. Machine learning is an effective way to estimate a car's price because it can analyse a car's features much more efficiently than humans can. This approach has already been used to analyse second-hand vehicle markets in countries such as the USA (Pudaruth, 2014), Switzerland (Bergmann and Feuerriegel, 2025), Croatia (Bukvić et al., 2022) and India (Semwal and Sharma, 2025). This study focuses on the Turkish used car market, which exhibits interesting dynamics.

Firstly, Turkey's rough terrain and uneven elevation make railway transportation difficult. Consequently, there is inadequate railway infrastructure, and most transportation takes place on roadways designed for cars (Keser et al., 2014). Secondly, demand for cars exceeds the supply of new cars (Lepan, 2020). The heavy tax burden on vehicle sales makes the car market more expensive than in most other countries. Hence, the second-hand car market plays a significant role in car ownership among citizens. This market reached an all-time high after the pandemic. During this period, the lack of new cars on the market led to second-hand cars being sold at a higher price than new cars.

Research on used-car valuation using detailed equipment data shows that including granular features materially improves resale-value forecasts. Bergmann (2025) demonstrates that moving beyond basic specifications and incorporating option-level detail yields significantly higher predictive accuracy than classical baselines, highlighting nonlinear and interaction effects among attributes. In parallel, official statistical agencies continue to rely on adjustments to build

used-vehicle price indices, confirming the centrality of age, odometer readings, and trim effects (United States Bureau of Labor Statistics, 2025).

On the machine learning side, comparative studies consistently find that ensemble models such as Random Forest and XGBoost outperform linear regression on structured car data (e.g. Chen, 2025). These methods capture nonlinear depreciation patterns and feature interactions, for example, the joint effect of year, mileage, and transmission type. Liu et al. (2022) report that engine power and new-car prices are strongly correlated with used-car values and that boosted models leverage these relationships more effectively than linear models.

Time-series forecasting offers another perspective, particularly when the target is the trajectory of prices rather than their current level. Comparative forecasting studies indicate that exponential-smoothing families, such as Holt–Winters, can rival or even surpass ARIMA and SARIMA for seasonal, evolving time series (Hyndman and Athanasopoulos, 2018). These results support the use of smoothing-based models when constructing indices or predicting resale values several months ahead. Still, when cross-sectional features are available, hybrid strategies that integrate Machine Learning (ML) with time-series methods tend to be the most effective (Bergmann and Feuerriegel, 2025).

The objective of this research was to understand the second hand car market in Turkey while also creating a model that is capable of helping potential buyers and sellers in this process of finding the correct price to sell in 2025. There have been previous studies about second hand car markets in other countries while Turkey doesn't have an up to date version of this study, we aimed to understand both the market and meanwhile creating a model to help people to gain on potential losses.

Dataset

In this study we employed the dataset Used Car Prices in Türkiye 2025 (EN/TR) (Kaggle), that provides a rich collection of attributes that can be used to train predictive models for Turkey's used-car market ("Used Car Prices in Türkiye 2025"). The data consists of 6675 cars that includes date, location, car brand, car specific characteristics and seller information. Location in data includes city and district information. Car brand includes information about brand, series and model. Car specific data are age, mileage(km), transmission type, fuel type, body type, color, engine size(cc), engine power(hp) and drivetrain. Seller data includes information about the seller type.

The dataset uses columns such as City which refer to the distribution of cars' location according to the Turkish Cities. Price(try) is the column which indicates the selling price of the car in Turkish Liras. As it is self explanatory, the brand column shows the brand of the car in sale. While year shows the year in which the car has been produced; and mileage gives the mileage in kilometers. Furthermore, transmission type determines whether the car is manual, semi-automatic or automatic, and like transmission type, fuel type categorizes the cars according to the fuel they use. The other categorical column is the body type; body type determines whether the car is hatchback, coupe, sedan or station wagon. The cars' body color is stored under

color, and the engine size of each given in cc is stored in engine size(cc). Similar to engine size, engine power(hp) stores the engine power in horsepower. Whether the car is All Wheel Drive or Forward Wheel Drive is stored under drivetrain. Finally, the seller type shows whether the seller is an authorized dealer, regular dealer or a private seller.

Exploratory Data Analysis

This section explores and discusses patterns and trends in the dataset. Observations from the dataset are studied using both categorical and quantitative variables. We aimed to understand the relationship between numeric (e.g. the price, engine power, age of the car) and categorical (eg. city of listing, drive train, brand type, color) variables in the dataset and their effect on the car price.

Figure 1 illustrates the count distribution of vehicle brands. It appears that only ten car brands hold the majority of the brand counts. The most frequent selling car in the dataset is Renault. Other frequently selling brands are Volkswagen, Fiat, Opel, BMW, Peugeot, Toyota, Ford, Hyundai, Audi and Volvo. The rest of the brands include less than 50 cars in the dataset.

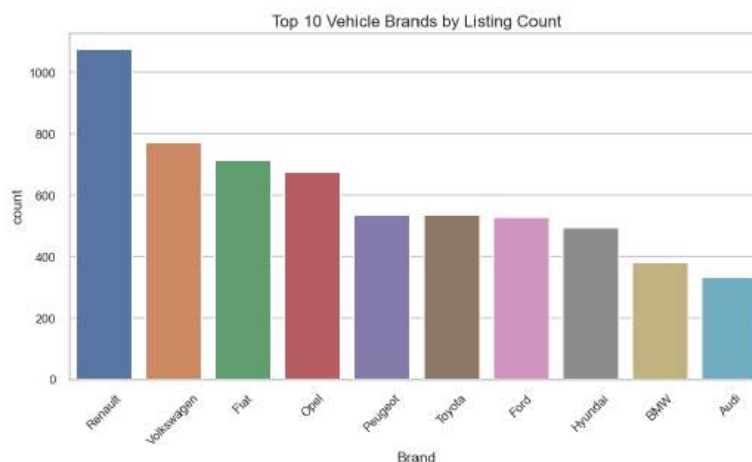


Figure 1. Count distribution of car brands

Figure 2 portrays the price distribution of car brands in the dataset. The boxplot shows which brands are more costly or more affordable. The eye-catching trend is that cheaper car brands usually have more outliers in the data, which shows that brands that usually have affordable prices sometimes produce luxury cars too. It also appears that on average the most expensive selling brands are Skoda, BMW and Audi.

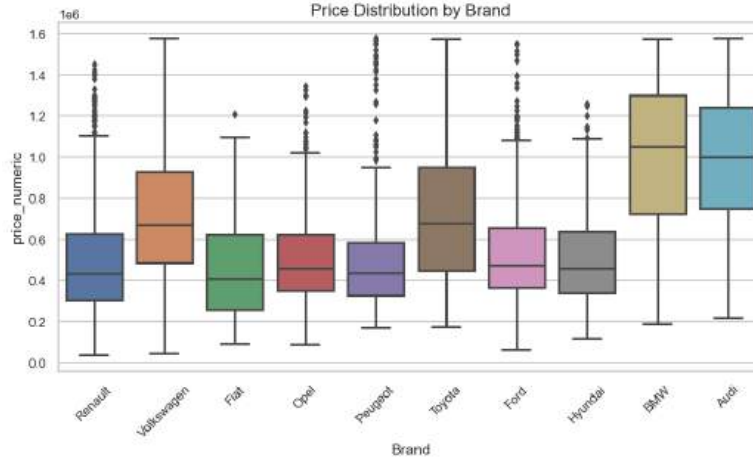


Figure 2. Price distribution of car brands

Figure 3 shows the correlation between the age and the price of the car. The graph portrays an exponential downward trend of the graph which illustrates that as a car gets older, its price decreases. The decrease gradually declines as the age increases. This observation is an expected behavior of the used car market in Turkey.

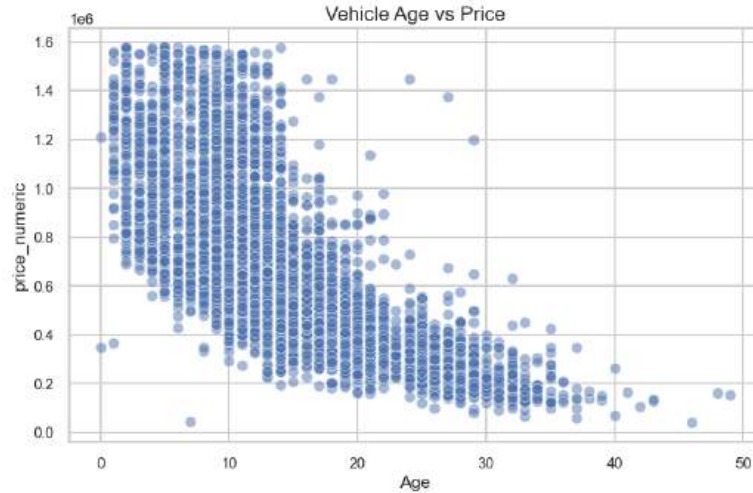


Figure 3. Relationship between price and age of the car

Figure 4 describes the relation between the mileage and the price of the car. The reduction of the car price as the mileage increases illustrates that the mileage of the car has a negative impact on the car price. This relation is also considered normal in the Turkey car market. Also some scatter of points seem to be outliers to the graph.

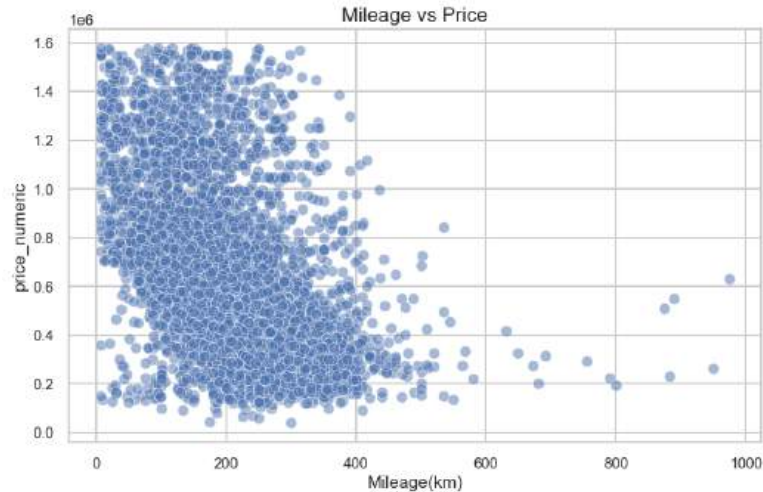


Figure 4. Relationship between price and mileage of the car

Figure 5 highlights the relation between engine size and price. Although the graph does not include a linear relationship, the vertical lines that are portrayed by the graph on particular engine sizes highlight the fact that specific engine sizes are more common in cars than other engine sizes. Also vertical clusters show that engine size does not affect the price of the car in a particular way.

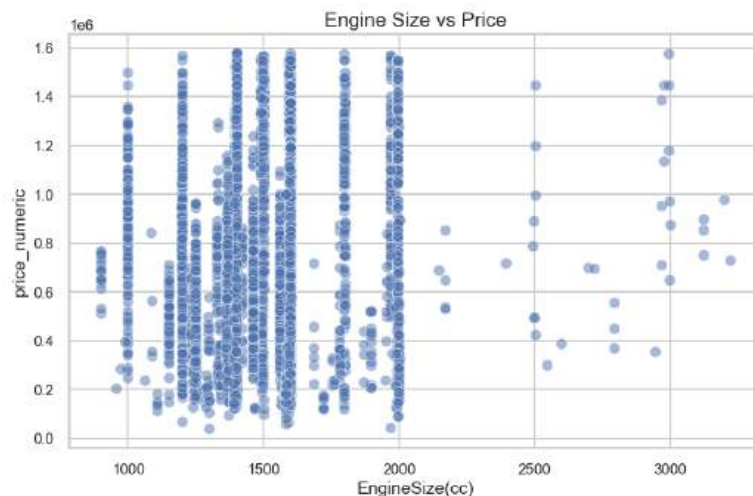


Figure 5. Relationship between price and Engine Size of the car

Figure 6 portrays the relation between engine power and price. The rise in car prices as the engine power increases portrays that the engine power of the car has a positive impact on the car price.

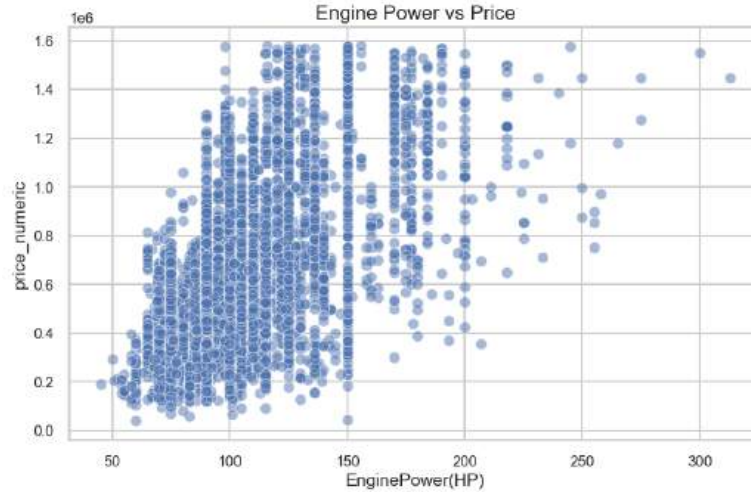


Figure 6. Relationship between price and Engine Power of the car

Figure 7 highlights the price distribution of the region of the car. The boxplots show the price ranges and the mean values for each region. Since the mean values are relatively close to each other the graph indicates that the mean value is not that much affected by the region, yet Marmara is the region with marginally higher mean price. This event is expected since the Marmara region includes the city Istanbul, a city which is considered an expensive city due to it being a metropol, and other high population cities.

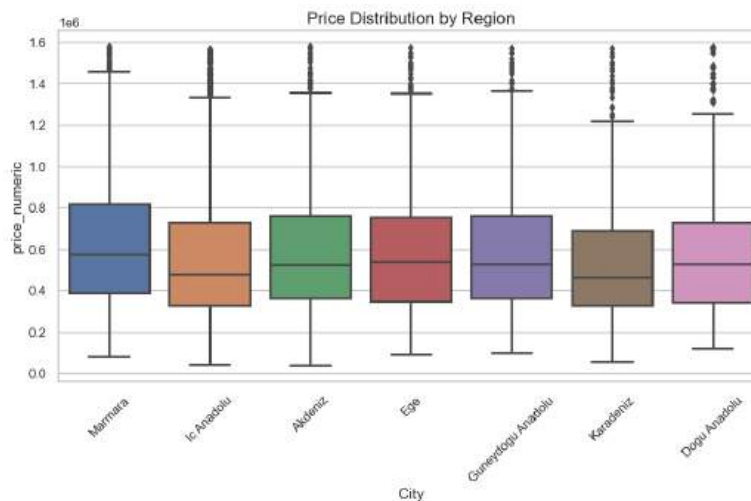


Figure 7. Price distribution by regions

Figure 8 portrays distribution of the number of listings for each region. The graph illustrates that Marmara is the region with the most listings. The cause for this event may be due to the Marmara Region holding most of the population in Turkey.

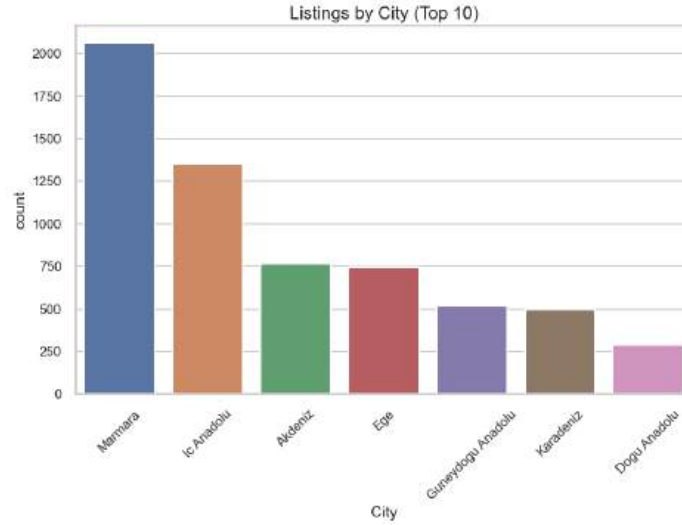


Figure 8. Count distribution of vehicle listings per region

Figure 9 illustrates the distribution of transmission types in the dataset. This graph shows manual cars are the majority in the dataset. Meanwhile automatic cars' count in the dataset with only $\frac{1}{3}$ of the manual cars' count. Furthermore, semi-automatic cars only have approximately 500 cars which makes semi-automatic cars the minority in the dataset.

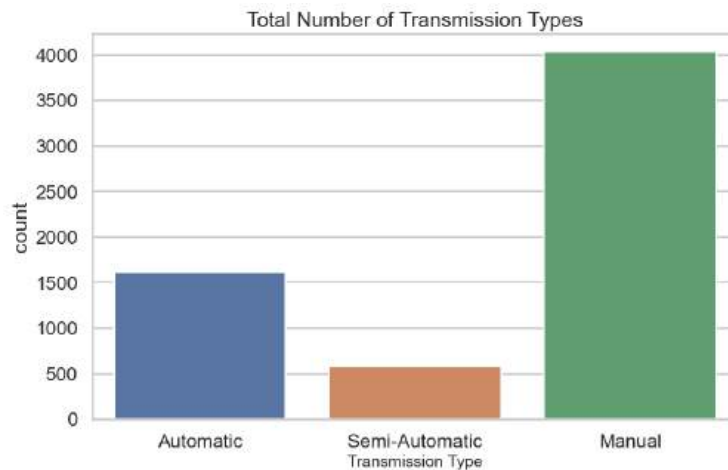


Figure 9. Count distribution of transmission types

Figure 10 shows the price distribution of the cars relative to their transmission types. This graph highlights the effect of transmission types on the car prices. Compared to mean prices, automatic cars are the most expensive and manual cars are the most affordable. The majority of being manual in Figure 10 can be explained by Figure 11. Since manual cars are cheaper it is expected for them to be more in the market.

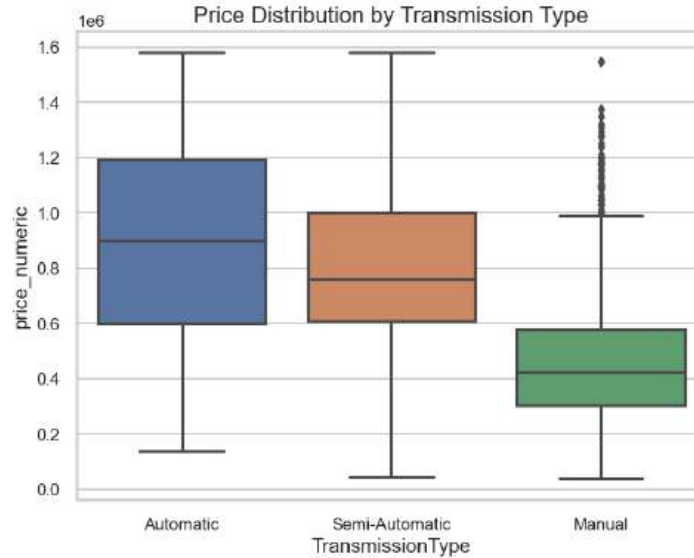


Figure 10. Distribution of price by transmission type

Figure 11 portrays the distribution of body types in the dataset. This graph shows that Sedans and Hatchbacks are the body types that are most seen in Turkey. Since there are some insignificant data points in some labels, we later group them as Hatchback (Hatchback/3 and Hatchback/5), Coupe(Coupe, Cabrio, and Roadster), Station Wagon(MPV and Station Wagon) and Sedan.

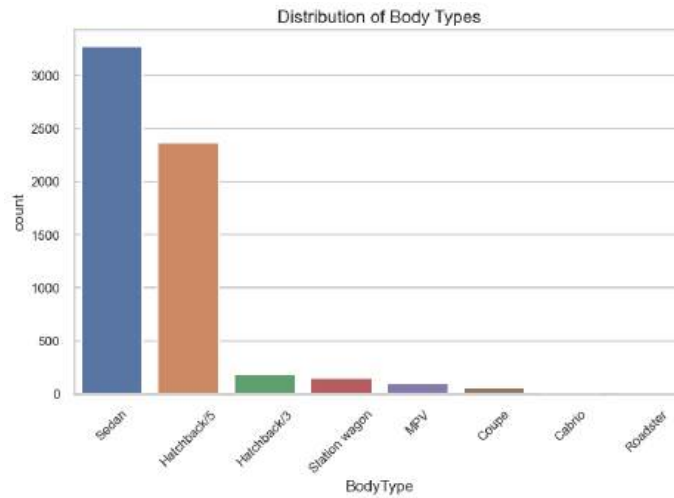


Figure 11. Count distribution of body types

Figure 12 highlights the distribution of price relative to the body type of the car. Coupe, Cabrio and Roadsters are the most expensive cars while Hatchback's, Sedans and Station Wagons are the least expensive cars. This explains the distribution in figure 12 as cheap hatchbacks and sedans are more seen in the dataset due to their affordability.

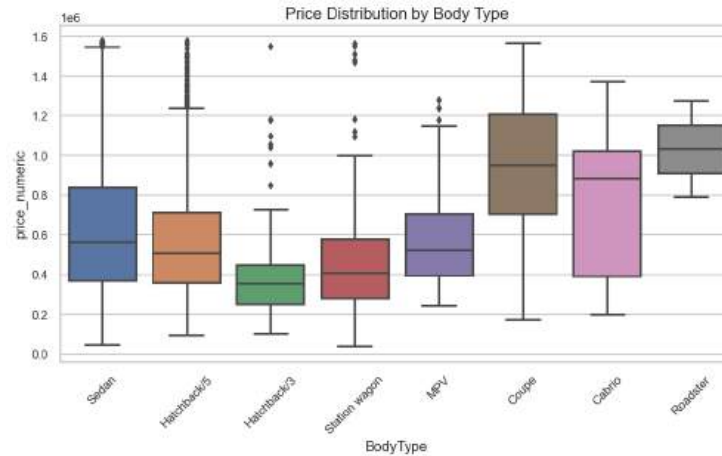


Figure 12. Distribution of price by body type

Figure 13 presents the Pearson correlation matrix for the numeric variables in the dataset. The results indicate that there are no variables with strong correlation exceeding ± 0.8 . Moderate negative correlations are observed between vehicle age and price, as well as between mileage and price, suggesting that older vehicles and those with higher mileage tend to have lower market values. A moderate positive correlation exists between engine power and price, reflecting the higher valuation of vehicles with greater performance capacity. Other relationships, such as between engine size and price, appear weak, indicating that these attributes contribute less directly to pricing compared to age, mileage, and engine power.

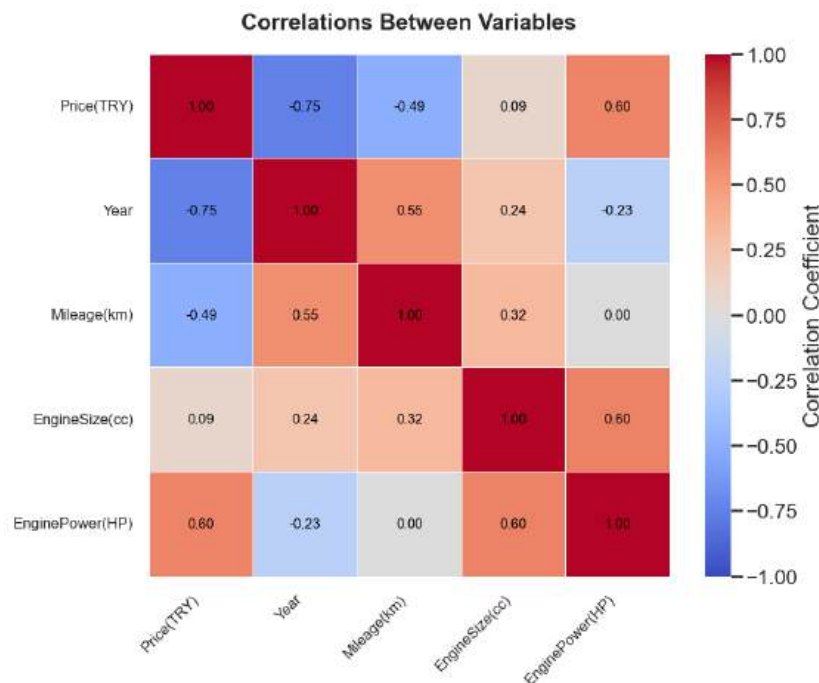


Figure 13. Correlation matrix between numeric variables

Methodology

Data Pre-Processing

The preprocessing step included mainly cleaning the data, removing missing values or columns and mapping selected columns based on exploratory data analysis. The following columns, "ListingTitle", "Series", "Model", "PaintAndPartsCondition", "ListingDate", "District", "ListingID", "TradeInAvailable", "VehicleTax(TRY)", and "AccidentHistory", were dropped due to significant number of missing values or irrelevant to our target car price prediction.

The city column included the 81 cities of Turkey. To simplify this column but keep the geographic information, we mapped it to the regions of Turkey, instead of the cities according to Figure 14 below. These regions are: “Marmara”, “Ege”, “Akdeniz”, “İç Anadolu”, “Karadeniz”, “Doğu Anadolu” and “Güneydoğu Anadolu”.



Figure 14. Map of Turkey divided into regions.

The color column included a wide range of colors. It was further simplified into similar groups of colors, such as white, gray, black, blue, green, yellow and red. The missing color values were replaced with the “Unknown” category. The body type column was grouped into subcategories based on the observations from Figure 11. Hatchback/5 and Hatchback/3 were grouped into hatchback, MPV’s were considered as Station Wagons, and Coupe, Cabrio and Roadster were all simply categorized as Coupe. The seller type column included categories such as authorized dealers, dealers and missing values. Authorized dealers and dealers were grouped into dealers category and missing values were replaced with “Unknown” category. Finally, in order for the model to process the categorical variables, one-hot encoding was done.

Input Feature and Output Target

The final input features selected for the model include both numeric and categorical variables that capture the main characteristics of vehicles listed for sale. These features are: city_region, brand, year, mileage_km, transmission_type, fuel_type, body_type, color,

engine_size_cc, engine_power_hp, drivetrain, and seller_type. Together, they provide comprehensive information about a car’s technical specifications, usage, and market context. The output target is car_price, representing the listed price of the vehicle in Turkish Lira (TRY), which the model aims to predict based on the given input features.

Table 1. Input features and output target

	Variable Name	Variable Type	Description
Output	car_price	Numeric	price of the car in Turkish Lira(TRY)
Input	city_region	Categorical	Geographic location of the car listing, mapped into seven Turkish regions (Marmara, Ege, Akdeniz, İç Anadolu, Karadeniz, Doğu Anadolu, Güneydoğu Anadolu).
	body_type	Categorical	Type of the car body, such as “Coupe”, “Hatchback”, “Wagons”
	seller_type	Categorical	Type of seller offering the car: dealer, private seller, unknown
	year	Numeric	The age of the vehicle
	mileage_km	Numeric	Vehicle mileage in kilometers
	transmission_type	Categorical	Transmission type of the car: manual, automatic or semi-automatic.
	fuel_type	Categorical	Fuel type of the car: diesel, petrol or LPG/Gas
	color	Categorical	Exterior body color of the vehicle, consolidated into groups
	engine_size_cc	Numeric	Engine size measured in cubic centimeters
	engine_power_hp	Numeric	Engine power measured in horse power
	drivetrain	Categorical	Drive system of the car, such as front-wheel drive or all-wheel drive
	brand	Categorical	Manufacturer of the vehicle (e.g., Renault, Fiat, Volkswagen, BMW)

Models and Evaluation Metrics

This study uses Linear Regression, Random Forest, and XGBoost methods to investigate the relationship between second hand car prices and corresponding car specifications. Before starting the model development process, 80 percent of the data was split into trains and 20 percent was split into tests.

The first model that was tested was Linear Regression. Linear Regression is suitable for continuous target variables, in our case, the selling price of a vehicle. While the linear regression model is suitable for continuous target variables, it is unable to understand and capture the complex, nonlinear relationships between variables. Therefore other models such as random forest and XGBoost were also tested. (Seber and Lee, 2012; Pedregosa et al., 2011)

Following the baseline linear regression model, a random forest regression model was applied. Random forest compiles multiple decision trees in order to enhance the predictive performance (Breiman, 2001; Pedregosa et al., 2011). Decision trees which are also used for prediction, include root nodes and leaf nodes. Each node answers a yes or no question which finally branches to the optimum answer. Each tree in a random forest for regression uses the average of the decision tree predictions for vehicle price (Hastie et al., 2005).

The last model which was trained was the XGBoost shorthand for eXtreme Gradient Boosting method. XGBoost also uses decision trees as its base learner like random forest; however, unlike random forest, XGBoost uses decision trees sequentially and improves the trees as it continues to advance by the sequence. As XGBoost creates newer decision trees, the quality of the decision tree increases. Creating a much more advanced and precise final prediction which takes the average of the created decision trees (Chen and Guestrin, 2016).

The models were evaluated using standard regression, including the coefficient of determination which is called R^2 . The R^2 value quantifies the proportion of variance in the price predicted by the linear regression model. The other two primary metrics which were used were mean absolute error (MAE) and mean absolute percentage error (MAPE). While MAE measures the average magnitude of the absolute differences between predicted and actual prices, MAPE expresses the error in percentage value instead of actual value in Turkish Liras.

Hyperparameter Tuning

Hyperparameter tuning was carried out to enhance the predictive ability of the ensemble models. Instead of relying on default parameter settings, which often lead to suboptimal performance, we systematically explored a range of candidate values using grid search combined with 10 times repeated 5-fold cross-validation (Pedregosa, 2011). This approach allowed us to balance bias and variance while ensuring that the selected models generalized well beyond the training data.

For the Random Forest Regressor, our focus was placed on three parameters: the number of trees in the forest ($n\_estimators$) were 100 and 500, the number of features considered at each split ($max\_features$) were between 2 and 32 with increment of 4, and the minimum number of samples required to divide a node ($min\_samples\_split$) were between 30 to 90 with increment of

10 as shown in Table 2. The grid defined broad ranges for each parameter, and the model was evaluated under each configuration using five-fold cross-validation repeated ten times. MAE was used as the optimization criterion during the search process, while final model performance was reported in terms of R^2 , MAE and MAPE. This process identified the configuration that minimized error while maintaining consistent performance across folds, reducing the chance of overfitting.

For the XGBoost Regressor, the parameter grid was expanded to include boosting-specific controls. We tested a range of learning rates (*learning_rate*) from 0.001 to 0.5, subsample ratios (*subsample*) between 0.5 and 1.0 with increment of 0.1, and feature sampling ratios at the node level (*colsample_bynode*) between 0.5 and 1.0 with increment of 0.1, along with boosting rounds (*n_estimators*) of 50, 100 and 500 as shown in Table 2. These parameters directly influence both the flexibility of the model and its ability to control complexity through regularization. A repeated 5-fold cross-validation scheme identical to that used for Random Forest was employed to ensure comparability.

Once the grid search was completed, the best-performing hyperparameter sets for both ensemble methods were selected and retrained on the full training data. Final performance was assessed on the test set using MAE and MAPE, supplemented by bootstrap resampling to quantify uncertainty of the test metrics (Pedregosa, 2011). This process demonstrated that careful hyperparameter tuning not only reduced prediction errors but also improved stability across different samples of the data.

Table 2. Model parameters and their value ranges

Model	Parameter	Value
Random Forest	n_estimators	[100, 500]
	max_features	between 2 and 32 with increment of 4
	min_samples_split	between 30 and 90 with increment of 10
Xgboost	learning_rate	[0.001, 0.005, 0.01, 0.05, 0.1, 0.2, 0.3, 0.5]
	subsample	Between 0.5 and 1.0 with increment of 0.1
	colsample_bynode	Between 0.5 and 1.0 with increment of 0.1
	n_estimators	[50, 100, 500]

Feature Importance Analysis

SHAP, short for SHapley Additive explanations, is a model interpretability approach grounded in cooperative game theory. It attributes a prediction to individual features by distributing the “payout” of the model’s output fairly among them, much like Shapley values in economics distribute rewards among players. This allows researchers to quantify both the

direction and magnitude of each feature's contribution, making SHAP particularly effective for explaining complex, non-linear models. SHAP analysis is a tool that helps viewers understand how complex machine learning algorithms make decisions (Lundberg and Lee, 2017). It does this by showing the importance of each feature and whether it has a positive or negative correlation. The reason why feature importance analysis has to be used in this study is to understand the importance of the features that the model has. SHAP analysis helps us to predict how the Turkish market is affected by the features we provided to the model.

Results and Discussion

The first approach in this study was the linear regression model. Table 3. shows that both the train R^2 values and test R^2 values are 85 percent. The model having almost similar R^2 values for the results implies that there is no overfitting in the model. The linear regression model also had MAE values of 91,560 TRY for train and 94,665 TRY for the test data. Mean Absolute Error(MAE) portrays that the linear regression model is for average 90,000 TRY away from the actual value of the selling price of the car. The test and train have a 3,000 TRY difference, which also further provides information that the overfitting is non-existent. Finally the MAPE values for the linear regression model was 19 percent for train and 21 percent for test. Shorthand version for Mean Absolute Percentage Error, MAPE values show that there is a twenty percent difference in the actual price and the predicted price of the car by the model. After trying the linear regression, we tried other models such as random forest.

After hyperparametrizing the random forest model, we managed to have a model which has almost a 90 percent R^2 for both train and test data with confidence intervals of 0.13 for train and 2.2 for test, showing the train having a much lower magnitude of variation from the mean R^2 compared to test. The best parameters for this model were max features of 18 which implies that the features that the model includes for its decision is 18. A min sample split of 30 which makes it so that each one of the trees will have at least 30 decision split nodes. And finally the number of estimators is set to 500, which indicates that the random forest includes 500 decision trees that will give an average result. Compared to the linear regression model, which had MAE values of 91,560 TRY for train and 94,665 TRY for test. The new hyperparameterized model has only 2 thousand turkish liras as difference. With train MAE being $70,683 \pm 4,105$ and test MAE being $72,424 \pm 4,511$ TRY, the confidence interval portrays that these values can vary almost up to 4500 TRY. This is an example of the random forest model reducing the previous issue of overfitting and high MAE. Furthermore the linear regression model previously had MAPE results of approximately 19 percent for train and 21 percent for test. The new hyperparameterized model recorded results of 13 ± 0.85 percent for train and 15.75 ± 3.81 percent for the test, the confidence intervals for the test imply that the test MAPE values' variation is high. These results also show the previous percentile difference degrading into approximately 13 and 15.75 percent with the help of the new hyperparameterized model.

While the Random Forest Model was an improvement compared to the very basic model of Linear Regression, the model could still be improved with the help of XGboost. After

hyperparameterizing the model, the R^2 value for the train was 93.13 ± 1.01 and for the test it was 91.7 ± 2.43 , showing that the confidence intervals, like the random forest model, were much more precise in train compared to test data. While XGboost had increased the precision of the model, the overfitting also increased to a difference of 1.5 percent between the train and test models. Also the previous MAE values for random forest and linear regression were 70,683 and 91,560 for train and 72,424 and 94,665 for test, respectively.(Table 3). As can be seen in Table 3, the train MAE value was $59,977 \pm 3,395$ TRY and the test MAE value was $64,044 \pm 4,392$ TRY. A further proof of XGboost decreasing the previous precision issue that was present in both linear regression and random forest model. Finally the MAPE XGboost values further decreased, making it 11.23 ± 0.6 for train and 14.16 ± 4.13 for test data. The high confidence interval of test data compared to the train data is still visible in XGboost as it was also in the random forest model as well.

While the models, linear regression and Random Forest were the least overfitting when compared according to the R^2 values. The XGboost model was the best model that provided the best results, for both train and test data. Even though this model achieved the highest precision, it overfitted almost 1 percent R^2 more compared to the other models.

When comparing the MAE values for the models. We can see that the Random Forest is almost 20,000 TRY better than linear regression when it comes to predicting the price of the car. And the XGboost model is closer to the actual value on average 10,000 TRY better than the Random Forest Model. Implying again that the XGboost's higher performance compared to other models.

Table 3. Evaluation metrics of model with corresponding confidence intervals

Model	Train/Test	R^2 (%)	MAE (TRY)	MAPE (%)
Linear Regression	Train	85.62	91,560	19.35
	Test	85.42	94,665	21.27
Random Forest <i>max_features = 18,</i> <i>min_samples_split = 30,</i> <i>n_estimators = 500</i>	CV Train	90.4 ± 0.13	$70,683 \pm 4,105$	13.15 ± 0.85
	Test	89.9 ± 2.2	$72,424 \pm 4,511$	15.71 ± 3.81
Xgboost <i>colsample_bynode = 0.5,</i> <i>learning_rate = 0.05,</i> <i>n_estimators = 500,</i> <i>subsample = 0.8</i>	CV Train	93.13 ± 1.01	$59,977 \pm 3,395$	11.29 ± 0.6
	Test	91.7 ± 2.43	$64,044 \pm 4,392$	14.16 ± 4.13

To interpret the outputs of the predictive models, we applied SHAP (SHapley Additive exPlanations), a method grounded in cooperative game theory that attributes each feature's contribution to the final prediction. SHAP values allow both a general perspective on which variables drive predictions across the dataset and a specified view of how individual features influence the price of a specific vehicle. Figures 15 and 16 summarize the general results for the tuned XGBoost Regressor.

The summary plot in Figure 15 illustrates that manufacturing year was the most influential predictor, with newer vehicles consistently associated with higher estimated prices, while older models exerted downward pressure. Engine power followed closely, as vehicles with greater horsepower tended to command premium valuations. Transmission type also emerged as a critical factor: manual transmissions generally contributed negatively to predicted prices compared to automatic alternatives. Mileage displayed the anticipated negative association, with higher odometer readings reducing estimated resale value.

Brand identity carried additional weight, particularly for Fiat and Renault, which showed measurable effects on price predictions. Fuel configuration, especially LPG and gasoline combinations, also played a role in differentiating vehicle values. In contrast, other features such as drivetrain configuration, seller category, and certain body types made relatively small contributions to the overall predictive performance.

The bar chart in Figure 16 ranks features by their average impact (mean absolute SHAP value), reinforcing that year, engine power, transmission type, and mileage dominate the pricing dynamics in this dataset. These findings reflect intuitive patterns in the automotive market: newer, more powerful vehicles with lower mileage and automatic transmissions are typically valued more highly, while older cars with extensive usage depreciate more quickly.

Taken together, the SHAP analysis demonstrates that the machine learning model captures relationships consistent with established market behavior while also highlighting brand- and fuel-specific influences that may reflect localized demand in the Turkish used car sector.

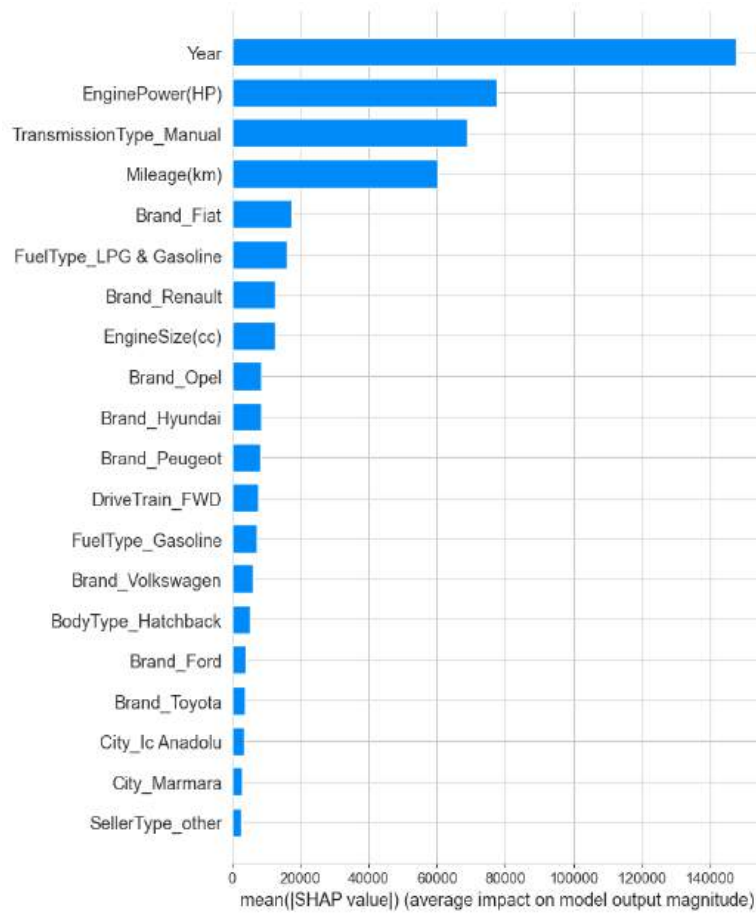


Figure 15. SHAP analysis for average impact on model output magnitude

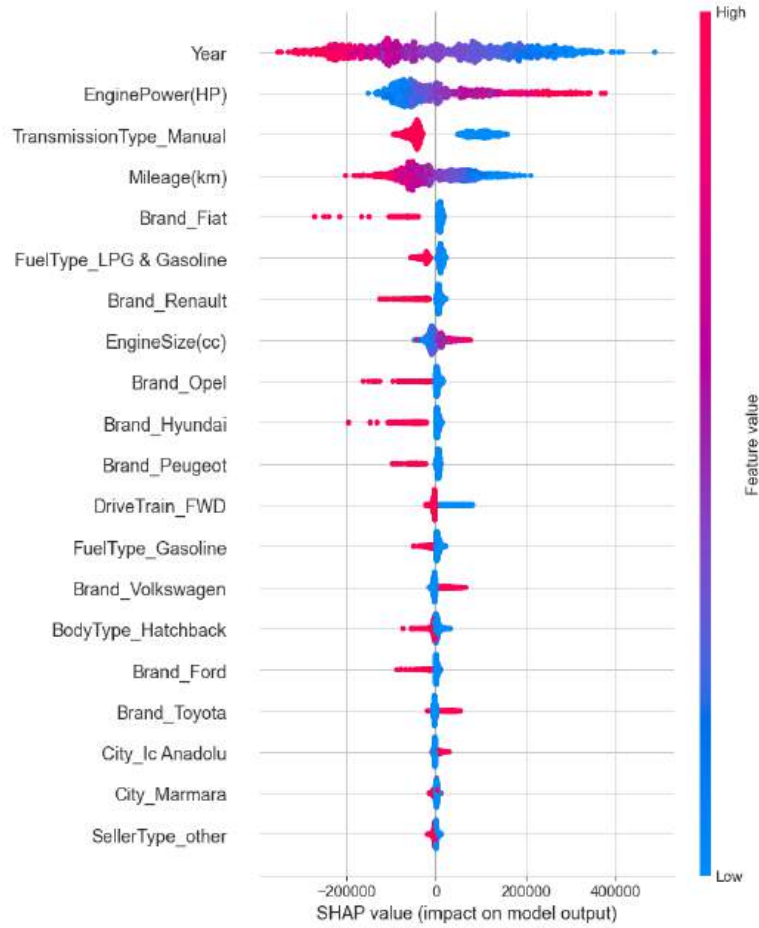


Figure 16. SHAP analysis for impact of features from individual sample on the model output

Compared to previous research, the results of this study show clear improvements in predictive accuracy. While linear regression in earlier Turkish studies reported R^2 values around 0.84 (Ulutürk, 2024) our tuned ensemble methods performed more consistently across test and validation samples. The Random Forest model achieved a bootstrapped test R^2 of 0.899, while XGBoost improved further to 0.917, with substantially lower MAE and MAPE values than baseline models. These results are in line with international findings that boosting methods outperform classical regressions in capturing nonlinear interactions among vehicle attributes (Liu et al. 2022).

The SHAP analysis further strengthens the contribution of this work by providing interpretable insights into the factors driving predictions. Consistent with the literature and economic expectations, variables such as year of manufacture, mileage, engine power, and transmission type emerged as the strongest determinants of vehicle value (Bergmann, 2025; United States Bureau of Labor Statistics, 2025).

Nonetheless, limitations remain. The dataset reflects vehicles listed in 2025 but includes postings from different periods, meaning inflationary pressures may distort price comparability. Future research could address this issue by incorporating dynamic inflation-adjusted pricing or

time-series corrections, as well as expanding the feature set to include macroeconomic variables and seller-specific characteristics. By combining robust predictive methods with interpretable outputs, this study contributes a replicable framework for price modeling in emerging second-hand vehicle markets.

Another limiting factor that we faced during this process was the fact that we had data from different regions of Turkey. Since the data was not distributed evenly, some regions had more data than others. If we had more data from other regions in Turkey, we could have had a better understanding of correlation between region and car price.

Conclusions

This study set out to explore the dynamics of Turkey's second-hand car market in 2025 and to develop predictive models that can assist buyers and sellers in determining fair vehicle prices. Using a dataset of 6,675 listings from Kaggle, we trained and compared Linear Regression, Random Forest, and XGBoost models. The baseline Linear Regression provided a useful benchmark but struggled to capture nonlinear patterns in the data. After systematic hyperparameter tuning, Random Forest achieved strong predictive power with a bootstrapped test R^2 of 0.899, while XGBoost outperformed all models with a bootstrapped test R^2 of 0.917 and lower MAE and MAPE values. These results demonstrate the advantage of ensemble methods in modeling the complex relationships that characterize vehicle pricing.

To interpret the model outputs, SHAP analysis was applied, revealing that year of manufacture, mileage, engine power, and transmission type were the most influential predictors of resale value. These findings align closely with established economic expectations and prior research, while also highlighting brand-specific and fuel-type effects distinctive to the Turkish market. Compared with earlier Turkish studies that relied primarily on regression-based approaches, our ensemble models offered higher predictive accuracy and more robust explanations.

Looking forward, the study's limitations suggest several directions for future research. First, inflation and economic volatility may have influenced vehicle prices during the data collection period, which warrants the integration of macroeconomic variables into future models. Second, the dataset was unevenly distributed across regions, limiting insights into regional price dynamics. Expanding coverage to underrepresented regions and incorporating temporal modeling could yield deeper understanding of market behavior. Finally, exploring hybrid models that combine ensemble learning with time-series forecasting may further enhance predictive accuracy in Turkey's rapidly evolving automotive market.

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AI and ML-Augmented Analysis for Precision Oncology and Cancer Diagnostics

By Ashvik Rao

ABSTRACT

Each year, nearly 20 million people are diagnosed with a form of cancer, and this number is expected to significantly increase. Despite hundreds of years of research on various cancers, the causes and genetic influences behind them are still not fully understood and current treatment options are, at times, unsuccessful. The recent development of artificial intelligence (AI) and machine learning (ML) tools has the potential to accelerate knowledge of and advancements in cancer screening, diagnostics, and treatment. AI can be incorporated into complex sequencing data sets and clinical imaging to allow for earlier detection of cancer. Similarly, by applying these tools to clinical data, AI and ML can drastically improve diagnostics, allowing for more accuracy in identifying cancer types. Additionally, AI and ML can greatly improve patients' prognoses by utilizing deep learning to predict patient response to different treatments. In this review, I will discuss the integration of AI and ML technologies into cancer screening, diagnostics, and therapeutic approaches to enhance precision medicine and treatment outcomes for cancer patients.

INTRODUCTION

Cancer is one of the leading causes of death worldwide with nearly 20 million new cases arising each year (National Cancer Institute, 2025). In the United States alone, approximately 2 million people were diagnosed with a type of cancer in 2024 (Collins, 2024). Of these, 600,000 are anticipated to die from the cancer itself or related complications. Despite billions of dollars in funding, progress in developing new ways to combat cancer has been slow. The lack of significant advancements underscores the need for new approaches and perspectives in cancer research. Traditional approaches, including surgery, chemotherapy, and radiation therapy, are often non-specific and maladapted to the high degree of variability observed amongst cancers. More effective, precise, and personalized approaches could lead to better patient outcomes and decreased rates of death.

Artificial intelligence (AI) and Machine Learning (ML) have emerged as powerful tools in healthcare, offering the potential to process and analyze massive volumes of data generated through clinical care, research studies, and patient monitoring. AI refers to the general ability of computer systems to mimic human intelligence, such as performing complex tasks, reasoning, pattern recognition, and decision-making (Columbia Engineering, 2025). ML, which is a subset of AI, involves the use of algorithms that learn insights and recognize patterns from data in order to maximize the performance of tasks. The use of ML allows machines to be trained to autonomously learn from past data with the goal of delivering accurate results. While ML relies on statistical models and has a more limited scope of applications, both AI and ML offer powerful benefits of integrating heterogeneous data and informing decision-making.

In healthcare, they are used to analyze complex information, such as genomic data and electronic health records (EHRs); identify patterns; and support faster, more accurate diagnoses and treatments. AI and ML have the potential to revolutionize cancer care by uncovering previously unknown oncogenes and tailoring care to individuals depending on their cancer

profiles, a strategy known as precision oncology. This could significantly improve diagnostic accuracy and reduce mortality. As AI and ML continue to expand and improve, it is critical to assess their impact on cancer care. In this review, I will examine the role of AI and ML in precision oncology, focusing specifically on their ability to improve cancer detection, diagnostic accuracy, and personalized treatment strategies.

MAIN TEXT

Revolutionizing Cancer Screening with AI and ML Technologies

Early cancer detection can improve survival rates, but traditional screening methods often miss subtle signs. Advanced tools such as AI and ML can enhance accuracy and efficiency of detecting these signs. Many new sequencing techniques, such as ARTEMIS and EPIC-seq, are being developed that allow for better detection of cancer DNA and the integration of AI and ML technologies.

DNA Analysis Techniques

ARTEMIS, which stands for Analysis of Repeat Elements in Disease, analyzes the parts of DNA that were once thought to have no function. These regions of non-coding DNA have been discovered to have specific functions and play a role in tumor cells. Parts of non-coding DNA have repetitive sequences, known as repeat elements, located throughout the genome, which have been found to be altered in cancerous tissue. ARTEMIS was designed to specifically identify these repeat elements, in addition to circulating cell-free DNA (cfDNA) - fragments of DNA shed from tumors that float in the bloodstream - in order to find tumor-specific changes in cancer patients (Annappagada et al., 2024). The ARTEMIS ML model was used to analyze over 1,200 types of repeat elements comprising nearly half of the entire human genome. It identified a large number of repeats that were altered in tumor formation (Johns Hopkins Medicine, 2024). When tested on patients with various cancers, ARTEMIS, when combined with another DNA fragment assay, was able to predict patients' tumor types with 75-85% accuracy. This technology allows researchers to analyze the entire genomes of patients in a fast and efficient manner, allowing for a noninvasive method to detect cancer.

Another sequencing method called epigenetic expression inference from cell-free DNA sequencing (EPIC-seq) was developed to detect cfDNA in the bloodstream. Similar to ARTEMIS, EPIC-seq aims to be a noninvasive method for cancer detection. Its ability to classify different tumor subtypes from just blood samples shows EPIC-seq's ability as a powerful tool in early, non-invasive cancer screening. This tool can be used to analyze biological markers faster, and more precisely, than traditional methods. EPIC-seq relies on sequencing the promoter regions of genes of interest of the cfDNA to predict differential gene expression in tumors (Esfahani et al., 2022). The sequencing results are then combined with machine learning to predict RNA expression and identify the tumor subtype. This method demonstrated high performance within cancer detection and tumor classification, with area under the curve (AUC) values above 0.9 for multiple cancer types. While EPIC-seq utilizes cell-free DNA, other AI models use other biological markers to detect tumors.

Epigenetic Targeting

DNA methylation represents a promising biomarker for revolutionizing cancer screening through AI and ML technologies, as tumors exhibit distinct methylation patterns that can be detected using computational approaches. While traditional methylation analysis has shown promise - such as a cervical cancer study that identified three methylation markers (GHSR, SST, and ZIC1) with ROC curve values between 0.86 and 0.89 for detecting precancerous lesions (Verlaet et al., 2017) - the integration of artificial intelligence has dramatically enhanced detection capabilities. A study demonstrated this potential by applying different AI algorithms, including support vector machines and deep learning, to DNA methylation patterns in circulating cell-free DNA from lung cancer patients (Bahado-Singh et al., 2022). These AI-driven approaches achieved exceptional performance with area under the curve (AUC) values of 1.00 and 100% sensitivity and specificity, representing a significant advancement over traditional screening methods. This integration of AI with epigenetic biomarkers exemplifies how machine learning technologies are transforming cancer screening by enabling highly accurate and minimally invasive detection methods that could revolutionize early cancer diagnosis.

Based on recent comprehensive research by Dr. Hajjar and colleagues, artificial intelligence and machine learning technologies are fundamentally revolutionizing cancer screening through multi-cancer early detection (MCED) tests that overcome traditional diagnostic limitations (Hajjar et al., 2024). These AI-augmented liquid biopsy platforms leverage sophisticated algorithms - including ensemble methods and deep learning - to analyze complex biomarker signatures from blood and urine samples, enabling simultaneous detection of multiple cancer types from a single test. Machine learning approaches have demonstrated remarkable performance with sensitivity ranges of 84-100% for early-stage cancers and specificity rates exceeding 98%, while AI-driven methylation pattern analysis has achieved clinical validation through FDA-approved tests like Galleri. Notably, multi-modal approaches integrating diverse biomarker types, such as the combination of protein markers with circulating tumor DNA and epidemiological data, have yielded superior diagnostic accuracy compared to single-biomarker strategies. This transformation from invasive, single-cancer screening to minimally invasive, AI powered multi-cancer detection represents a paradigm shift toward precision oncology, offering the potential to dramatically improve early detection rates and save lives through quick intervention.

The integration of artificial intelligence and machine learning technologies has transformed cancer screening methodologies, offering unprecedented capabilities in early detection through advanced genomic analysis. AI algorithms excel at processing the massive datasets generated by next-generation sequencing, enabling more accurate and efficient identification of cancer causing variants through improved variant-calling techniques such as DeepVariant, which outperforms standard tools in detecting significant genetic alterations (Lin et al., 2022).

Revolutionary screening approaches now leverage liquid biopsy technology, where AI facilitates the analysis of circulating tumor cells, extracellular vesicles, and tumor-derived cell-free DNA (cfDNA) found in blood and other bodily fluids, providing a less invasive

alternative to traditional tissue sampling (Ginghina et al., 2022). Multi-cancer early detection (MCED) tests utilize AI to analyze methylation patterns indicative of cancer in cfDNA from asymptomatic populations, with machine learning algorithms processing the vast amounts of data to enable timely analysis and intervention (O'Connor & McVeigh, 2025). Advanced AI models like AlphaMissense can predict the pathogenicity of all possible missense variants in the human genome at a single amino acid substitution level, allowing clinicians to identify and screen for clinically relevant pathogenic variants with unprecedented precision (Cheng et al., 2023). Computer vision applications further enhance screening capabilities by analyzing histopathological and radiological images to predict genetic mutations within tumors, as demonstrated by models that can determine EGFR mutation status in non-small-cell lung cancer from CT and PET scan images (Popat et al., 2025). These AI-driven screening innovations collectively enable earlier cancer detection, more comprehensive genomic profiling, and the potential for population-wide screening programs that could greatly improve patient outcomes through timely intervention.

AI and ML-Powered Advances in Cancer Diagnostics

AI and ML are transforming diagnostics by making detection faster, more accurate, and more personalized. These technologies can analyze vast amounts of complex data, including medical scans, genetic profiles, and pathology slides, to uncover patterns that may be difficult for human experts to detect. Recent advances have demonstrated how AI can improve diagnostic precision, classify cancer subtypes more effectively, and predict treatment outcomes. As these tools continue to evolve, growing attention is being placed on how AI and ML models, such as Explainable AI, can help patients receive more efficient diagnoses.

The Use of Explainable AI

Explainable AI (XAI) helps patients receive faster diagnoses by making complex machine learning predictions more transparent and actionable for clinicians. A comparison of multiple XAI platforms used on breast cancer datasets revealed one superior AI model, SHapley Additive exPlanations (SHAP), that was able to clearly present model outputs in simpler terms for clinicians to understand (Ghasemi et al., 2024). By showing how specific features, such as biomarkers or clinical variables, contribute to a diagnosis, SHAP allows healthcare providers to interpret AI-generated results while also having a clearer understanding of the process that the AI model used to generate those outputs. This interpretability builds trust in the model's findings, enabling doctors to make faster and more confident decisions. As a result, patients can move more quickly from initial screening to diagnosis and treatment, reducing delays that could potentially worsen patients' outcomes. In time-sensitive conditions like breast cancer, this acceleration in the diagnosis process can make a critical difference in prognosis, highlighting how XAI not only improves model transparency but also has a direct impact on patient care. In addition to faster diagnoses, AI is also being used to anticipate complications during treatment, helping to predict negative side effects that can result from these life-saving therapies.

Targeting Specific Cancer Types

AI is also being used to support treatment continuity by predicting and preventing

complications that might otherwise delay or interrupt therapy. In a phase 3 randomized controlled trial, researchers evaluated the use of romiplostim (ROMI), a thrombopoietin receptor agonist, to address chemotherapy-induced thrombocytopenia (CIT) in patients with gastrointestinal cancers. CIT is a common and serious side effect of chemotherapy that can lead to dose reductions, delays, or even discontinuation of treatment, potentially compromising patient outcomes. The study found that patients receiving ROMI were significantly more likely to avoid CIT-related chemotherapy modifications compared to those receiving placebo - 84% versus 36%, respectively (Al-Samkari, 2025). This kind of clinical challenge is increasingly being addressed with AI models that can anticipate risks, like CIT, based on patient data. When integrated into care, such predictive tools can help providers make early decisions, such as adjusting therapy or preemptively introducing supportive treatments like ROMI, to keep patients on track. This demonstrates the growing role of AI in optimizing treatment strategies, a trend also reflected in recent breakthroughs in personalizing therapies for many other cancer types. Recent advances show that AI can also play a critical role in identifying which patients are most likely to benefit from specific cancer therapies, helping to personalize treatment while avoiding unnecessary side effects. In a large international study, researchers developed an AI tool that analyzes tumor biopsy images to predict which patients will respond best to abiraterone - a widely used drug for treating prostate cancer. Although abiraterone has already improved survival for many with advanced disease, it also comes with risks such as high blood pressure, liver abnormalities, and increased chances of heart problems (Gregory, 2025). The AI test identifies a subgroup of patients - about 25% - who are most likely to benefit from treatment, with data showing the drug cut their five-year mortality risk nearly in half (Gregory, 2025). Meanwhile, for patients unlikely to benefit, the tool helps avoid overtreatment by showing that standard therapies alone are sufficient. This approach reflects a broader shift toward AI-powered precision medicine, where treatment decisions are guided not just by clinical guidelines but by individualized predictions derived from routinely collected data. By enabling clinicians to match therapies more effectively to each patient's specific disease profile, AI helps improve outcomes, reduce toxicity, and make better use of healthcare resources.

Pancreatic cancer - particularly pancreatic ductal adenocarcinoma (PDAC) - remains one of the most aggressive and lethal forms of cancer, with a five-year survival rate of just 13% (American Cancer Society, 2025). Diagnosis is especially difficult due to vague early symptoms and a lack of reliable screening methods, resulting in 80-90% of patients being diagnosed at an advanced stage when curative treatment is no longer an option. Although CT imaging is the most commonly used modality for initial evaluation and offers a sensitivity of 70-90%, its diagnostic effectiveness is limited without advanced analytical support (Chen et al., 2016). To address these challenges, one study presents a deep learning-based diagnostic system that integrates Convolutional Neural Networks (CNN) with a YOLO-based CNN architecture (YCNN) to enhance early detection of PDAC (Dinesh et al., 2023). By analyzing CT scans and identifying cancerous features using pixel-level classification, the system demonstrated superior performance, achieving F1-scores of 0.99 and 1.00 in detecting and grading pancreatic cancer. The model processes images by dividing them into 224×224 pixel patches, classifying them, and then reconstructing the complete image for review by pathologists, offering both precision and

interpretability. The use of platforms like PyCharm and Google Colab streamlines development and accessibility, and the authors propose future enhancements including data augmentation, expanded datasets, and synthetic image generation guided by specialists. Ultimately, this AI powered system holds promise as a practical diagnostic aid, capable of providing consistent second opinions through a user-friendly web interface and improving the early detection and classification of pancreatic cancer.

The Use of Omics Data

Machine learning is now underpinning major advances in cancer diagnostics by enabling integration of heterogeneous omics data - genomic, transcriptomic, proteomic, and more - into unified analytical frameworks. According to Dr. Cai and colleagues, these approaches are generally grouped into general-purpose methods, which combine dimensionality reduction with downstream modeling, and task-specific models, which are end-to-end tools tailored to particular applications (Cai et al., 2022). Central to this integration is the strategy known as middle integration, which avoids naive feature concatenation while consolidating signals across omics layers through machine learning, mitigating the curse of dimensionality common in multi-omics datasets. The review also benchmarks five tools, including DIABLO, MOFA2, iClusterPlus/Bayes, and moCluster, used on data from the Cancer Cell Line Encyclopedia, evaluating for their accuracy in cancer type classification and drug response prediction, as well as runtime performance. Notably, DIABLO, a supervised method that leverages label information, like tissue type, achieved the highest cancer-type prediction accuracy (78.7%), underscoring how integrative ML models can more precisely classify tumor subtypes compared to conventional unsupervised approaches (Cai et al., 2022). These developments illustrate how AI-driven integration of multi-omics datasets delivers richer molecular diagnostics, enabling identification of distinct cancer subtypes, more accurate treatment stratification, and ultimately a path toward truly personalized oncology.

AI and ML Applications in Tailored Cancer Therapies

Artificial intelligence and machine learning are playing an increasingly important role in developing and refining cancer treatment strategies. By processing large-scale data from clinical records, genetic information, and histopathological images, AI/ML models can identify complex patterns that predict how individual patients will respond to specific therapies. This allows for more personalized and effective treatment plans, going beyond generalized protocols. From enhancing chemotherapy response predictions to identifying biomarkers for immunotherapy, AI and ML are accelerating the shift toward precision oncology.

Predicting Patient Response to Treatment

One example of this progress is a new AI tool that predicts which cancer patients are most likely to benefit from immune checkpoint inhibitors, which are a type of immunotherapy drug, using only routinely collected clinical data (Chang et al., 2024). These therapies help the immune system recognize and attack cancer cells, but their effectiveness varies widely between individuals. Existing tests to predict treatment response are often expensive or unreliable. To address this, the team created a ML-based scoring system called LORIS (Logistic Regression

based Immunotherapy-response Score), which uses six routinely collected clinical features: tumor mutational burden, patient age, cancer type, history of prior therapies, blood albumin levels, and blood NLR (a measure of inflammation). After evaluating data from over 2,800 patients with 18 different cancer types, LORIS outperformed existing models in predicting both short- and long-term outcomes. Its simplicity and accessibility make it a promising tool for guiding personalized treatment decisions in everyday clinical practice. Beyond tools like LORIS, broader applications of AI are also advancing immunotherapy by identifying predictive biomarkers and new therapeutic targets.

A similar machine learning system has been built by Dr. Chowell's team out of the Icahn School of Medicine at Mount Sinai called SCORPIO (Standard Clinical and labOratory featuRes for Prognostication of Immunotherapy Outcomes). SCORPIO predicts how well cancer patients will respond to immune checkpoint inhibitors using only basic, routinely collected clinical data, such as blood counts and metabolic profiles (Yoo et al., 2025). Unlike traditional biomarkers such as evaluating tumor mutational burden and PD-L1 expression - which are expensive, time consuming, and not widely available methods - SCORPIO uses accessible data and outperforms these methods in predicting patient response. Validated on nearly 10,000 patients across 21 cancer types, SCORPIO represents a scalable and cost-effective tool that could expand access to precision oncology, especially in limited-resource conditions. Additionally, SCORPIO has the capability to accurately predict survival rates of patients over the course of 2.5 years, with performance rates of about 75%. Researchers emphasize its potential to reduce unnecessary treatments, improve outcomes, and promote equitable cancer care by making personalized treatment decisions possible in daily clinical practice.

Artificial intelligence and machine learning are changing how we approach personalized cancer treatment by making it possible to tailor therapies with incredible precision. In cancer treatment, especially chemotherapy, AI helps analyze how medications interact with individual patients, making sure treatments are given effectively while predicting how well patients will tolerate and respond to them (Abdul Rasool Hassan et al., 2025). These AI tools excel at processing huge amounts of patient information – including genetic profiles, biomarker levels, and medical histories – to figure out the best treatment combinations and predict how each person will respond. Machine learning can spot complex patterns in tumors and patient biology that doctors are rarely able to catch on their own, leading to better drug options, optimized doses, and precise timing of treatments. Additionally, AI systems are continuously learning from treatment results across thousands of patients, allowing them to improve prediction accuracy, find alternative ways to target cancers, and assist with overcoming drug resistance. This smart approach to cancer care represents a major shift away from the old "same treatment for everyone" model to truly personalized medicine, where treatment decisions are made by sophisticated algorithms that consider both the unique fingerprint of each person's cancer and their individual medical background.

AI is also being used to support treatment continuity by predicting and preventing complications that might otherwise delay or interrupt therapy. In a phase 3 randomized controlled trial, researchers evaluated the use of romiplostim (ROMI), a thrombopoietin receptor agonist, to address chemotherapy-induced thrombocytopenia (CIT) in patients with

gastrointestinal cancers. CIT is a common and serious side effect of chemotherapy that can lead to dose reductions, delays, or even discontinuation of treatment, potentially compromising patient outcomes. The study found that patients receiving ROMI were significantly more likely to avoid CIT-related chemotherapy modifications compared to those receiving placebo - 84% versus 36%, respectively (Al-Samkari, 2025). This kind of clinical challenge is increasingly being addressed with AI models that can anticipate risks, like CIT, based on patient data. When integrated into care, such predictive tools can help providers make early decisions, such as adjusting therapy or preemptively introducing supportive treatments like ROMI, to keep patients on track. This demonstrates the growing role of AI in optimizing treatment strategies, a trend also reflected in recent breakthroughs in personalizing therapies for many other cancer types.

The Use of Deep Learning

A novel deep learning (DL) model demonstrates how artificial intelligence can significantly enhance treatment prediction for patients with metastatic clear cell renal cell carcinoma (ccRCC), the most common and lethal form of kidney cancer. ccRCC is typically treated with anti-angiogenic (AA) therapies, which aim to block the formation of new blood vessels feeding the tumor. However, due to substantial variability in tumor vascular architecture and gene expression, identifying which patients will benefit from AA therapy has remained a major clinical challenge. Traditional approaches, such as RNA-based tools like the Angioscore, provide some predictive power but are expensive, time-consuming, and sensitive to tumor sampling variability. To overcome these limitations, researchers developed the H&E DL Angioscore using a convolutional neural network trained on routine hematoxylin and eosin (H&E)-stained pathology slides (Jasti et al., 2025). This AI model automatically quantifies angiogenesis and generates a continuous score that predicts patient response to AA therapies. In both real-world and clinical trial cohorts - including the IMmotion150 trial - the model performed comparably to the RNA Angioscore (c-index 0.66 vs. 0.67) and outperformed conventional vascular biomarkers like CD31 immunohistochemistry (Jasti et al., 2025). Beyond its predictive accuracy, the model produces visually interpretable vascular heatmaps that highlight intra-tumoral variation, making its output more clinically transparent and trustworthy. By enabling fast, scalable, and cost effective assessment of tumor angiogenesis, the H&E DL Angioscore represents a powerful step forward in personalizing treatment for renal cancer patients and optimizing the use of AA therapies in clinical practice.

Traditional cancer treatment strategies, such as those based on maximum tolerated dose (MTD), often fail in the metastatic setting due to rapid emergence of drug resistance. To address this limitation, researchers developed a deep reinforcement learning (DRL) framework designed to optimize adaptive therapy (AT), an approach that delays resistance by maintaining a population of drug-sensitive cancer cells to suppress resistant ones (Gallagher et al., 2024). Using a virtual cohort of prostate cancer patients, the study trained DRL agents on tumor dynamics simulated by mechanistic mathematical models. These agents learned personalized treatment schedules that significantly outperformed both MTD and commonly used AT strategies, including outperforming AT50 in delaying disease progression. Notably, the DRL policies required only a single input – the tumor burden threshold – and were interpretable,

allowing clinicians to understand and trust the model's decisions. Even when trained without full knowledge of the tumor model, the DRL framework achieved robust and clinically relevant outcomes, highlighting its flexibility. To support clinical translation, the authors proposed a five-step pathway emphasizing mechanistic modeling, DRL training, and clinical interpretability. This work shows how AI-guided strategies can transform cancer care by adapting therapy to the evolving dynamics of each individual patient's disease. Together with earlier advances in drug response prediction and treatment stratification, these innovations demonstrate that AI is reshaping cancer therapy into a more dynamic, data-driven process. As machine learning models grow more interpretable and clinically validated, they are poised to become essential tools in designing effective, patient-specific treatment plans.

CONCLUSION

The growing integration of AI and ML into cancer research and care is reshaping how clinicians detect, diagnose, and treat malignancies. In screening, these technologies have advanced the analysis of genomic, epigenetic, and molecular data, enabling earlier identification of cancer related patterns that may be missed by traditional approaches. In diagnostics, AI has improved the accuracy of classification, integrated diverse biological datasets, and provided explainable outputs that enhance trust in clinical settings. In treatment, AI models, including deep learning, have optimized therapy schedules, predicted patient-specific drug responses, and tailored interventions to tumor dynamics. Together, these developments mark a decisive move toward precision oncology, where care is increasingly proactive, data-driven, and individualized.

The advantages of AI and ML in oncology are substantial. They allow rapid processing of high dimensional data, reveal patterns invisible to human interpretation, and offer the potential for more accurate and timely decision-making. Personalized approaches informed by AI can reduce overtreatment, improve survival outcomes, and enhance quality of life. However, limitations remain. Many AI models are developed on controlled datasets that may not reflect the complexity of real-world patient populations. Data privacy concerns, potential biases in training datasets, and limited interpretability in some algorithms can hinder clinical adoption. Additionally, the need for large, high-quality annotated datasets presents logistical and ethical challenges that must be addressed.

To make these technologies mainstream, several steps are essential. Rigorous clinical validation across diverse populations is needed to confirm the reliability and generalizability of AI models. Interdisciplinary collaboration between clinicians, data scientists, and regulatory bodies will be important to ensure that algorithms meet both performance and ethical standards. Efforts to improve model transparency and interpretability will foster clinician and patient trust. Integrating AI tools into existing healthcare infrastructure, supported by data governance frameworks, will further smooth the transition from research to clinical practice. As these requirements are met, AI and ML have the potential to become indispensable components of oncology, delivering real benefits to cancer patients worldwide.

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Predicting Alzheimer's Disease Risk with Machine Learning Models Using Behavioral and Psychological Indicators By Mahee Patel & Mr. Odysseas Drosis

Abstract

Alzheimer's disease (AD) is a progressive brain disorder that damages memory, thinking, and overall quality of life. Current ways of diagnosing AD often involve invasive tests or costly brain scans, which can delay early treatment. Machine learning (ML) provides a possible way to predict AD risk using simple behavioral and psychological factors. This study tested whether five ML models—linear regression, decision tree, random forest, neural network, and K-Nearest Neighbor—could predict AD status based on three main variables: behavioral problems, sleep issues, and depression scores. A publicly available dataset ($N = 2,149$) was used and split 67% for training and 33% for testing. The models were judged by accuracy, precision, recall, and F1-score. The linear regression model reached 67% accuracy, with good performance on AD-negative cases but weak results on AD-positive cases. The decision tree scored highest at 81% but showed signs of overfitting. Random forest (78%) and neural network (75%) had more balanced results, while KNN was lowest at 67%. A simple majority-voting method improved accuracy to 75%. All models showed difficulty handling the uneven number of AD-positive and AD-negative cases, seen in lower recall for the AD-positive class. These results suggest that ML models, especially combined methods, could help predict AD risk using non-invasive data. Still, better input variables, balanced datasets, and more testing are needed before the models can be applied in real clinical settings.

Key Words

Alzheimer's disease, early detection, machine learning models, artificial intelligence, prediction models, neural networks, decision tree, k-nearest neighbor, random forest, behavioral factors, depression, sleep disturbance, cognitive decline, accuracy score, majority vote scheme

Introduction

Through this research paper, various artificial intelligence (AI) machine learning (ML) models will be tested to determine how well AI can be used to diagnose Alzheimer's Disease (AD) based on metrics including AD prognosis and associated risk factors, preventive factors, and clinical assessments. The ML models utilized include the linear regression, decision tree, random forest, neural network, and K-Nearest Neighbor (KNN) models. These models will be used to evaluate whether or not a patient has Alzheimer's Disease given the patient's behavioral problems, sleep quality, and depression or lack thereof. The models' predictions will then be used to determine the strengths and limitations of using AI ML models to detect early onset Alzheimer's in clinical settings.

Literature Review

Alzheimer's disease is increasingly being studied for early signs of cognitive decline, which can show up as behavioral issues, changes in sleep patterns, and depression.

Sleep quality is a factor strongly associated with risk for developing AD. Disrupted sleep, specifically reduced slow-wave sleep and interrupted rests, has been linked to impaired production of the β -amyloid and tau proteins, important signs of AD (Ju et al., 2019). Furthermore, self-reported insomnia and irregular sleep patterns correlate with accelerated cognitive decline, even in otherwise healthy older adults (Spira et al., 2013). Although sleep disturbances may also result from natural neurodegeneration, its role as an early symptom highlights the importance of incorporating sleep statistics in predictive AI technology.

Behavioral issues such as irritability, agitation, and personality changes have also been recognized as key markers of early-onset AD. These neuropsychiatric symptoms are often signs of mild cognitive impairment (MCI) and can lead up to other symptoms such as memory loss (Ismail et al., 2016). Studies show that behavioral changes correlate with neurodegeneration in frontal and temporal regions, suggesting that they may provide early insight into disease progression (Canevelli et al., 2013). Additionally, behavioral symptoms are often reported by caregivers before cognitive testing detects abnormalities, making these accounts and symptoms valuable in early detection.

Depression has been repeatedly associated with a higher risk of developing AD. Meta-analyses suggest that late-life depression almost doubles the likelihood of later AD diagnosis, possibly due to overlapping neurobiological issues such as hippocampal atrophy, dysregulated cortisol pathways, and chronic inflammation (Diniz et al., 2013). While some researchers argue that depression may act as a preliminary symptom rather than a causal factor, longitudinal studies continuously highlight its importance for predicting cognitive decline (Ownby et al., 2006).

Lately, research has been focusing more on finding early, non-invasive ways to predict AD, since most diagnoses only happen after a lot of brain damage has already occurred (Kale et al., 2024). Artificial intelligence (AI) is showing the most promise in improving early detection by analyzing patient data. AI can identify biomarkers that indicate early stages of AD and integrate multiple sources of information, such as cognitive assessments, lifestyle factors, and symptom reports, into predictive models (Kale et al., 2024). Studies also suggest that machine learning models can analyze changes in sleep and other behavioral indicators linked to MCI, demonstrating the potential of computational tools to combine different types of early warning signs into a single predictive AI model.

By combining cognitive and behavioral markers with AI analyses, researchers can detect early Alzheimer's more accurately than relying on a single symptom. Using data like depression, behavioral problem, and sleep quality symptoms with AI biomarker analyses allows for a stronger and more complete understanding of early disease progression and allows for earlier interventions.

Material and Methods

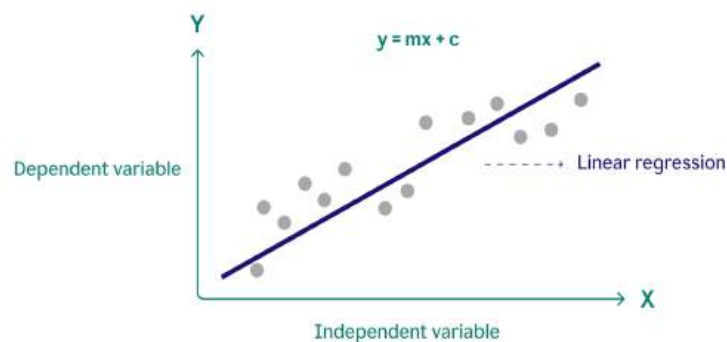
The Alzheimer's Disease Dataset contains data from 2,149 patients, including demographic characteristics (age, gender, BMI, ethnicity, education level), lifestyle and health factors (smoking, alcohol consumption, physical activity, diet quality, sleep quality), medical history (family history of Alzheimer's disease, cardiovascular disease, diabetes, depression, head injury, hypertension), clinical measures (blood pressure, total cholesterol, LDL, HDL, triglycerides), and cognitive or functional assessments (Mini-Mental State Exam, functional assessment, memory complaints, behavioral problems, activities of daily living). It also records Alzheimer's-related symptoms such as confusion, disorientation, personality changes, difficulty completing tasks, and forgetfulness. Diagnoses of conditions (e.g., head injury, diabetes, confusion, and Alzheimer's disease) are recorded on a binary scale, with 0 indicating absence and 1 indicating presence. This study specifically examines how behavioral problems, depression, and sleep quality are associated with a positive (1) or negative (0) diagnosis of Alzheimer's disease.

In order to test the accuracy of each model, the dataset was split into training and testing data, with 67% of it used for training and the other 33% for testing. The training data was used to allow each model to learn how behavioral problems, sleep quality, and depression influence diagnosis of AD. The testing data was then used to evaluate the performance of each model on unfamiliar data to provide an unbiased measure of accuracy.

The models implemented include a linear model, decision tree, random forest, neural network/multi-layer perceptron (MLP), and K-nearest neighbors.

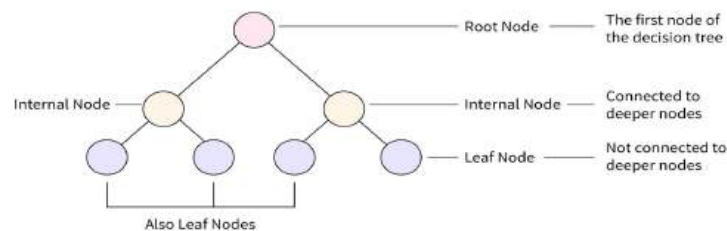
A linear model is one of the simplest methods for making predictions. This model works by multiplying each input by a specific weight and then adding them together to produce a result. There are no hidden layers or complex steps involved, making the model easy to understand and quick to use. However, due to its simplicity, linear models can often miss patterns or disregard complexities when relationships between variables are not linear, assuming that each input directly and independently affects the outcome. An example of a linear model is seen in Figure 1.

Figure 1:



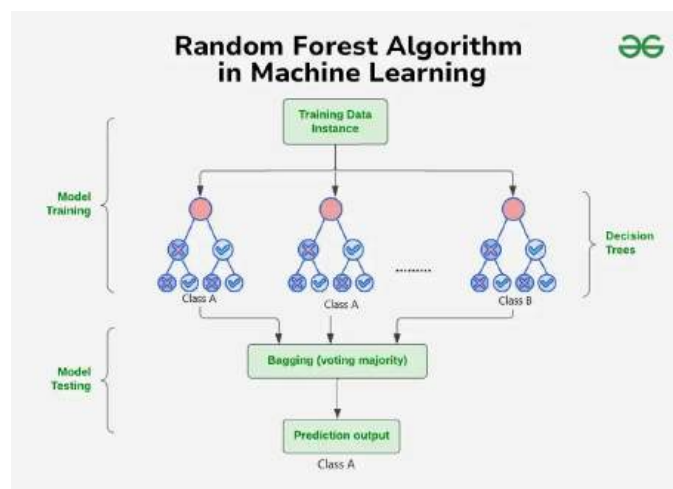
A decision tree makes predictions by following a series of “yes or no” questions based on input values. Each answer leads to another question until the model reaches a final decision. For example, if a condition is met, it might result in “green,” and if not, “red.” This structure makes decision trees easy to interpret, similar to the structure of a flowchart (see Figure 2). However, trees that are too deep or complex can become overly specific to the training data, reducing their accuracy on new testing data.

Figure 2:



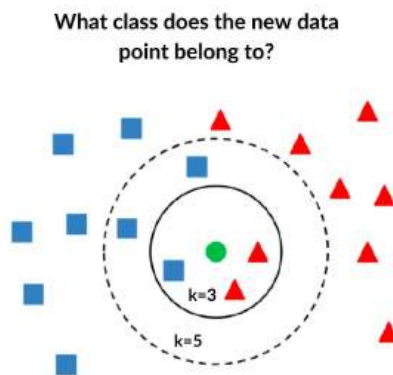
A random forest improves on a single decision tree by using many decision trees at once. Each tree gives its own prediction, and the random forest combines them, often by averaging, to make a more accurate final prediction. Important choices include how many trees to use and how deep each tree should be. This approach helps reduce errors caused by randomness and generally produces more reliable results than using one tree alone. A random forest algorithm example is shown in Figure 3 below.

Figure 3:



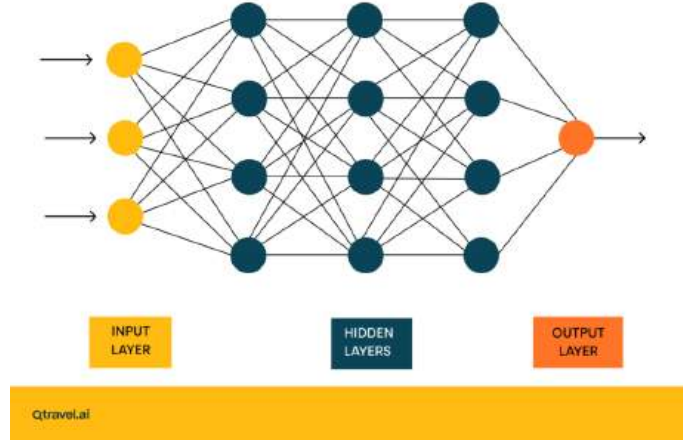
K Nearest Neighbors (KNN) makes predictions by looking at the data points closest to a new point. The model checks the K nearest neighbors and uses the majority label among them to make a prediction. Choosing a small K can make the model overly sensitive to noise, while a large K might include less relevant points. Closer neighbors can also be given more weight to improve accuracy. KNN works well when patterns are not linear but can become slow or less effective when handling large amounts of data. An example of a KNN model is seen in Figure 4 below.

Figure 4:



A neural network is modeled after the human brain and uses layers of connected nodes, called neurons. Each neuron calculates a value based on input weights, and those values pass through the network in steps. The model starts with random weights and adjusts them gradually to improve accuracy (see Figure 5 below). Key settings include how many hidden layers there are, how many neurons are in each layer, and how many times the weights can be adjusted. Neural networks are especially strong at dealing with complex patterns but often require adjusting and more computational power.

Figure 5:



To combine the predictions from these different models, a majority vote scheme was used. In this method, each model gives a prediction for a patient, and the final classification is the one that most models agree on. For example, if three out of five models predict Alzheimer's-positive and two predict Alzheimer's-negative, the final prediction would be positive. We also used a weighted majority vote, where models that performed better during training had more influence on the final prediction, giving more reliable models extra weight in deciding the outcome.

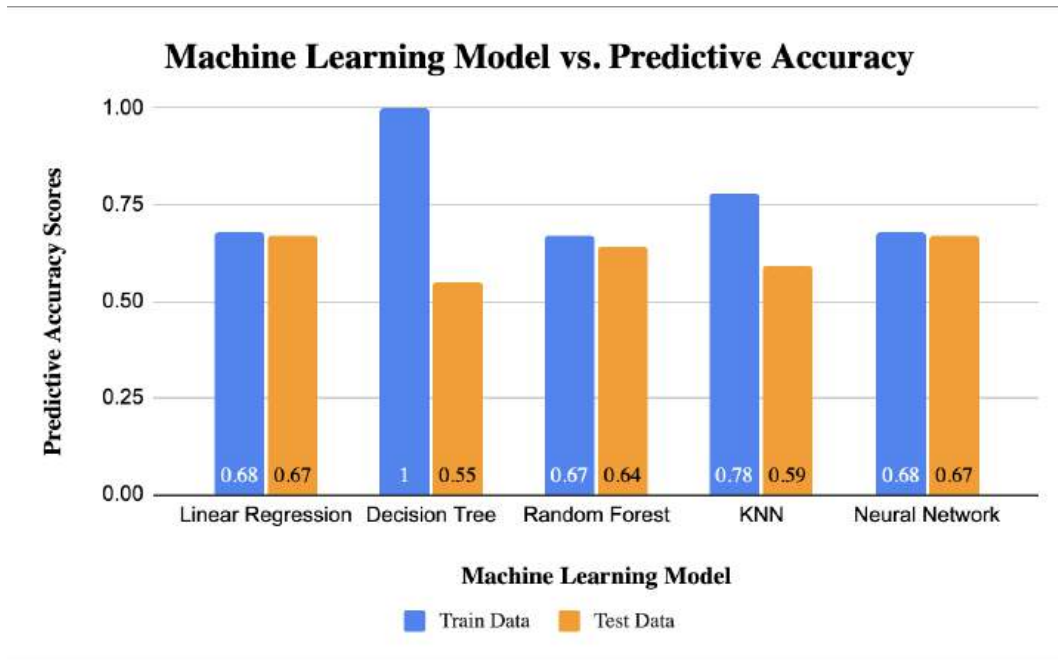
Model performance was primarily evaluated using an accuracy score, which measures the percentage of correct predictions out of all predictions made. In other words, it reflects how often the model correctly classifies a patient as Alzheimer's-positive or Alzheimer's-negative depending on the given diagnosis from the dataset. Since our dataset is balanced between positive and negative cases, accuracy provides a simple way to compare the effectiveness of each model and the majority vote scheme.

Results

Figure 6: Machine Learning Models Vs. Predictive Accuracy Table

Model	Train Accuracy	Test Accuracy
Linear Regression	0.68	0.67
Decision Tree	1.0	0.55
Random Forest	0.67	0.64
KNN	0.78	0.59
Neural Network	0.68	0.67

Figure 7: Machine Learning Model vs. Predictive Accuracy Graph



The performance of the five machine learning models varied in accuracy and generalization ability (Figure 6). The decision tree reached 100% accuracy on the training data but decreased to 55% on the test data, which suggests that it overfit to the training set. In contrast, the neural network and linear regression models both reached 67% accuracy on the test data, showing that they were better generalized than the decision tree model.

The random forest model performed slightly lower, with a test accuracy of 64%. However, it demonstrated very high precision in predicting the negative class, meaning it was effective at identifying patients without Alzheimer's disease. The K-Nearest Neighbor (KNN) model showed the weakest results with only 59% accuracy, making it the least reliable of the five models analyzed.

Additional classification reports are included in the appendix. These show that the models generally had higher precision and recall for the negative class compared to the positive class. This indicates that the models had more difficulty identifying Alzheimer's cases than non-Alzheimer's cases.

Discussion

The observed performance of the five machine learning models shows noticeable differences between the training and test data. Linear regression and the neural network models performed the best, where each showed a 67% accuracy on the test set. Both models were better at identifying patients without Alzheimer's, but they struggled more with correctly classifying those with Alzheimer's.

The decision tree model, on the other hand, clearly overfit the training data, achieving 100% accuracy on the training set but only 55% on the test set. This suggests that the model

memorized the training data but was not able to generalize this information well to apply to new patients' diagnoses. The random forest model improved on this by averaging predictions across multiple decision trees, achieving 64% accuracy on the test set. It showed high precision for non-Alzheimer's patients but still incorrectly classified many patients with AD. The K-Nearest Neighbors (KNN) model had moderate performance, with 59% accuracy. While it correctly identified some Alzheimer's-positive cases, it was sensitive to random errors in the data and was inconsistent in its predictions.

To help balance predictions across models, a majority vote scheme was applied, where each patient's predicted label was determined by the class most models agreed on. Using this method, the weighted accuracy reached around 66%, slightly improving overall reliability. Even though this compound evaluation did not surpass the top individual models, it provided a more consistent prediction and demonstrates the potential for combining models to improve early Alzheimer's detection in future research.

Conclusion

Overall, the machine learning models were able to identify patterns in behavioral problems, sleep quality, and depression that relate to early Alzheimer's risk. While accuracy was moderate and some positive cases were missed, these results suggest that AI could be a promising tool for non-invasive early detection. Even with limited behavioral and cognitive features, meaningful patterns can be captured to provide insight into early-stage Alzheimer's.

However, there are important limitations to consider. This study only included behavioral problems, depression, and sleep quality from the full dataset, so it may not fully capture all early indicators of Alzheimer's. Additionally, imbalances between patients with and without Alzheimer's likely reduced the models' ability to detect positive cases, and differences in performance on unseen data highlight the challenge of generalizing from more complex medical datasets with less features.

Despite these limitations, the findings show the potential of AI to enhance early Alzheimer's detection. Expanding datasets and machine learning models to include and analyze additional predictive data such as electroencephalograms (EEGs), sleep structure, or other neuroimaging could improve accuracy. Future research could also explore more advanced models or intersect methods to reduce false negatives and improve generalizability. Overall, this established the possibilities of using behavioral and cognitive information in AI Alzheimer's research, emphasizing the need to refine methods and expand data to develop more useful predictive tools in clinical settings.

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Exploring and Comparing Current and Emerging Sources of Sustainable Aviation Fuels (SAFs): Challenges, Solutions, and Pathways to Net-Zero Emissions by 2050

By Pak Ying (Sophie) Wong

Abstract

The aviation sector has played an increasing role in global warming as it is one of the hardest-to-abate sectors in reducing carbon emissions. With air travel demand expected to exceed 20 billion passengers by 2050, achieving net-zero carbon emissions by that year is a critical challenge. Efforts have been made to reduce its carbon footprint to achieve net-zero carbon emissions by 2050. Sustainable Aviation Fuel (SAF) offers a promising solution, potentially reducing lifecycle CO₂ emissions by up to 80% compared to conventional jet fuel, and is compatible with existing aircraft infrastructure. Despite its potential, SAF meets only 0.53% of the global jet fuel needs. To advocate for the deserved awareness and higher resources for SAF technology, this paper reviews the diverse feedstocks and technological pathways for SAF production. It also examines the key challenges, which include feedstock constraints, high production costs, limited capacity, and lack of standardization frameworks. In addition, it proposes solutions that include alternative feedstocks, government incentives, decentralized production, and global regulatory harmonization. These efforts are essential to make SAF commercially viable and support the aviation industry's decarbonization goals.

Introduction

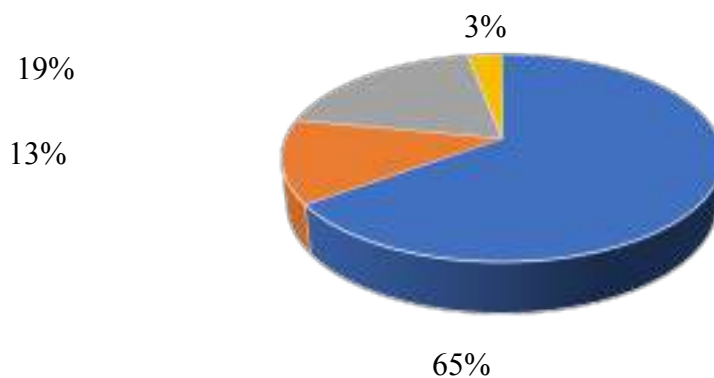
Air transport has promoted globalisation and economic growth, and enabled people to travel around the globe. However, it has also imposed serious impacts on the environment. The global aviation industry was responsible for around 2.5% of the global carbon dioxide emissions in 2023 and approximately 4% of global warming (Our Commitment) (Expected Sustainable). The Airports Council International (ACI) estimates that the global passenger traffic reached 9.5 billion at the end of 2024, and the demand for air passenger journeys in 2050 could exceed 20 billion in 2050 (Bauen). The expected 2021-2050 carbon emissions on a 'business as usual' trajectory will reach 21.2 gigatons of CO₂ (Cabrera).

As per the forecast by the World Economic Forum in 2023, experts predicted that the global carbon emissions from the aviation industry will increase at a disproportionate rate, as the other sectors decarbonise faster (Our Commitment). Aviation could account for up to 22% of global carbon emissions by 2050 (How all Sustainable), an alarming figure that gets significant public attention, making solutions to aviation decarbonisation even more urgent.

The aviation sector is taking several sustainability measures to address the environmental concerns. Some are related to in-flight sustainable options, while others are more towards improving operational efficiency. Some airlines aim to reduce single-use plastics such as water bottles, utensils, amenities, and packaging items (Eytan). Some provide locally-sourced and seasonal foods to reduce the carbon footprint from food transportation (Eytan). Some airlines also offer options for passengers to invest in carbon offset projects to offset the carbon

emissions released during travel (Saddler). There are also incentives to encourage passengers to travel light, as lighter aircraft result in less fuel consumption (Campbell). Other operational improvements to increase efficiencies, such as optimizing flight routes for minimum emissions and improving maintenance schedules, can also contribute to reducing the carbon footprint (SAF Capacity). However, all the above practices are not sufficient to achieve the net-zero carbon emission goal, as the vast majority of aviation-related greenhouse gas comes from traditional jet fuel.

In 2021, IATA member airlines signed a commitment to achieving net-zero carbon emissions from their operations by 2050. Per IATA estimates, SAF will make a 65% contribution towards the net-zero carbon emission goal. The rest of the 35% will come from new technology at 13%, offsets and carbon capture at 19%, and infrastructure and operational efficiencies at 3% (Cabrera). As the CO₂ emissions by air travel come primarily from fossil fuel consumption, sustainable aviation fuel (SAF) is still by far the most important and effective way to reduce the carbon footprint. In this paper, the focus is on the CO₂ emissions instead of the other byproducts coming from jet fuel.



Sustainable Aviation Fuel New technology, electric and hydrogen

Offsets and carbon capture Infrastructure and operational efficiencies

Fig 1: Contribution to achieving Net Zero Carbon in 2050 (Our Commitment)

What is SAF?

Sustainable Aviation Fuel (SAF) is an alternative fuel that can be used by aircraft to reduce CO₂ emissions by up to 80% (How all Sustainable). This alternative fuel can be produced from the biomass taken from different feedstocks. During the production cycle, biomass feedstocks will absorb CO₂ from the atmosphere. When SAF is burned during aviation travel, it will release the same amount of CO₂. Thus, from a bio-lifecycle perspective, there is no additional CO₂ emission from the use of SAF (Imtisal). On the contrary, traditional jet fuel, using fossil fuels, will emit a high amount of greenhouse gas when they are burned. Use of jet fuel will also release carbon dioxide and other byproducts that contribute to global warming. SAF can be used in today's aircraft without changes to existing storage, delivery, and filling systems (Zehua) (What is Sustainable). Currently, SAF can be blended with traditional jet fuel

in a maximum ratio of 50% as per the American Society for Testing and Materials Standard (ASTM) and can decrease CO2 emissions by up to 40% (SAF Handbook).

Despite the potential of SAF, we are only in the early stages of SAF adoption in the aviation sector. In 2024, SAF production capacity was estimated to be close to 1.5 million metric tons (Mt), which met around 0.53 percent of total jet fuel needs for the year, according to IATA estimates (RSB). There is a need for the relevant governments and regulatory bodies to formulate strategic roadmaps and milestones to develop SAF on a sustainable basis in the next 25 years. To reach net zero by 2050, the expected SAF required will be close to 450 billion litres of SAF annually (What is eSAF?). Such volume translates to at least 10,000 production facilities required, while there are only more than 350 production facilities around the globe that can produce SAF to reduce carbon emissions (Niels) (Joe). As per International Civil Aviation Organization (ICAO), the United States has the largest number of SAF production facilities, followed by Canada, France, and the United Kingdom.

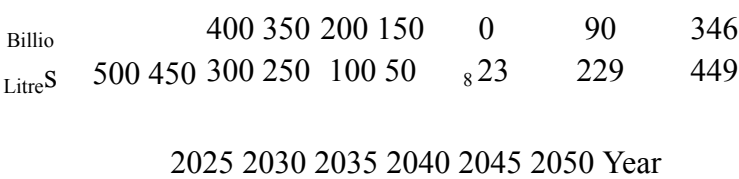


Fig 2: Expected SAF Required for Net Zero 2050 (Expected Sustainable) Types of SAF feedstocks and associated technology

First generation feedstocks

SAF can be made from a variety of production sources. The majority of the current SAF used today is bio SAF, which is derived from biological sources. The first generation feedstocks used to produce bio SAF include edible food related fats and oils such as canola, palm oil, and corn (What is Sustainable). But there is a limitation in supply as using food related fats and oils for producing SAF creates supply challenges by putting SAF in competition with food production (What is Sustainable) (Kyle). As a result, fuel producers are turning into second generation feedstocks for a more sustainable SAF production (Kyle).

Second generation feedstocks

The second generation feedstocks refer to non-edible waste oils and fats such as used cooking oils, inedible animal fats, and industrial wastes (What is Sustainable). The second generation feedstocks are generally more sustainable than first generation feedstocks. They also do not compete with food production and food security, and are relatively more readily available. They are critical in the current stage of SAF production in meeting the decarbonisation goal.

Third generation feedstocks

There are also third generation feedstocks that include agricultural wastes, municipal solid wastes, and forestry residues (What is Sustainable). They are abundant in nature, especially in regions like Southeast Asia, where they can potentially meet significant SAF demand (Brendan). But the technologies for converting agricultural residues into SAF are still developing, with ongoing research in optimizing these processes to achieve efficiency and scalability (The Price).

Hydroprocessed Esters and Fatty Acids (HEFA)

In terms of technology, the primary pathway used to produce SAF from edible fats and oils, used cooking oils, animal fats, and wastes is Hydroprocessed Esters and Fatty Acids (HEFA) (Imtisal). HEFA is an established technology, and it involves hydroprocessing oils and fats to produce Synthetic Paraffinic Kerosene (SPK), which can be blended with conventional jet fuel up to a maximum limit of 50%. HEFA is scalable due to its compatibility with existing refinery infrastructure (The Price) (Li). It is worth noting that it is generally more expensive to produce SAF from second generation feedstocks than first generation feedstocks, as they require further processing before they can be converted to biofuel. But it is more environmentally friendly as those used cooking oils and waste oils would otherwise have been discharged to water or landfills (Kyle). The HEFA pathway is a mature technology and is commercially viable, which has been successfully used in numerous flights (The Price). For instance, Virgin Atlantic, Emirates Airlines, Cathay Pacific, Lufthansa, and Ryanair have started to use SAF produced by HEFA. However, due to the large amount of SAF production required to meet the 2050 net-zero carbon emission goal and the inconsistency in supply quality for the SAF production, supply constraint is a major issue (Kyle) (What is Sustainable).

Alcohol-to-Jet technology (AtJ)

The second technological pathway to produce SAF is Alcohol-to-Jet technology (AtJ). It is used to turn feedstocks such as sugarcane (What is Sustainable) and corn grain (The Price) into SAF. This technology can turn sugars or lignocellulosic carbohydrate based sources into bioethanol or isobutanol that can then be converted into SAF (What is Sustainable) (Riefer). ATJ has a maximum blending ratio of 50% (The price). However, there is a sustainability concern related to the use of food crops (Riefer). The cost of bioethanol or isobutanol conversion needed for the approved SAF production process is another issue, given that the production of cellulosic ethanol from lignocellulosic feedstock is complex (Riefer). In addition, as the feedstocks supply has been used for other fuel production, there is a limited supply available for the production of SAF (Scaling Up Sustainable).

Fischer-Tropsch Technology (FT)

The third technological pathway is Fischer-Tropsch Technology (FT). It uses biomass from agricultural and forestry residues and converts them into SAF after processing (What is Sustainable) (The Price). FT can be blended up to 50%, but has the potential to replace

traditional fuel in full 100% in the future (SAF Capacity). There are clear environmental benefits associated with this technology, as the wastes used in this pathway come from landfills (The Price). However, it is more difficult to convert these residues than waste oil to SAF because the physical properties of the feedstocks require more pre-treatments before thermochemical or biochemical processing (Bastin). In terms of production cost, FT is more expensive than HEFA and AtJ technologies. It is capital-intensive to build the infrastructure (The Price). Given this cost hurdle, R&D efforts are being pursued to develop more cost-efficient FT technology that will enable SAF production to be more economic and scalable in the future (The Price). In particular more work needs to be done on the design and economic viability of scaling down processes for biomass and waste-based systems and the overall efficiency of an integrated system (Bauen).

Current status of feedstocks and technology applications

Based on the current SAF research & development cycles, the majority of SAF will still be produced from biomass with inedible feedstocks, in which used cooking oil, waste fat, and oils stand out in the near future as the most promising feedstocks. Though the edible feedstocks, such as oilseeds, are still the cheapest method to produce using HEFA technology, these food crops do compete with land usage and food production, and thus are not being used in scale. Among the three technological pathways discussed, HEFA has been more widely adopted today to produce SAF, driven by lower capital costs and availability of inedible feedstocks (SAF Capacity). It is also the only commercial pathway being deployed at scale now to produce SAF. It offers a cost-effective solution for SAF production due to higher yield and low fuel costs (Wen). However, limited supply availability of current feedstocks is a key hurdle to scale-up adoption (The Price).

Table: Summary of different technological pathways, feedstocks, constraints, and considerations

Technological Pathway	Possible Feedstocks	Maximum Blending Ratio (Cabrera) (How all Sustainable)	Constraints	Other Considerations

HEFA	• Edible food related vegetable oils and fats (What is Sustainable) • Non-edible, such as used cooking oil (What is Sustainable)	50%	• Edible food competes with food production (What is Sustainable) (Eytan) • Used cooking oil has limited supply (What is Sustainable) (Eytan)	• Only SAF production technology at commercial scale (How all Sustainable) • Cheaper to produce SAF from edible food fats and oils (Eytan) Used cooking oil is more environmentally friendly (Eytan)
AtJ	• Ethanol and isobutanol from sugarcane and corn grain biomass (What is Sustainable) (Saddler)	50%	• Sustainability concerns related to the use of food crops (Saddler) • Limited supply (Campbell)	• The cost of conversion is higher than HEFA (Saddler)
FT	• Agricultural and forestry residue (What is Sustainable)	50%	• Difficulty in conversion • More expensive than HEFA and AtJ (How all sustainable)	• More environmental benefits (How all sustainable)

Key challenges with SAF production and associated solutions

1. Structural feedstock constraints

There are several key challenges associated with making SAF production commercially viable. First of all, bio-SAF has structural feedstock constraints as the edible food feedstocks compete with the production supply to feed the human population, while the supply of fats, oils, and greases compete with the production of other renewable diesel and biodiesel products (SAF Capacity). So governments typically discourage the use of food crops due to concerns over deforestation and food security. Thus, the industry has been looking for more diverse sources of alternative supplies and technologies to produce SAF on a large scale.

Potential solutions

More efforts have been put into exploring and identifying alternative feedstocks that align with government sustainability criteria. For instance, alternative feedstocks such as microalgae are being explored due to their fast growth rate and their effectiveness in reducing carbon dioxide in the atmosphere (Imtisal). Microalgae are more expensive than traditional feedstocks due to high cultivation and processing costs, but it does offer high yield potential per acre (How all Sustainable) (Zehua). Microalgae can be cultivated on non-arable land, reducing competition with food crops (How all Sustainable). Once the supply of alternative feedstocks becomes more abundant, it would alleviate the pressing feedstock supply issue.

Apart from bio-SAF, the industry is exploring the use of non-biological feedstocks to produce SAF, and it is called synthetic SAF or e-fuel. Synthetic SAF can be produced from renewable energy. It can use renewable hydrogen obtained through electrolysis, which splits water into hydrogen and oxygen using electricity generated from renewable sources such as wind, solar, or hydroelectric power. This hydrogen is then combined with CO₂ to create synthetic fuels (What is sustainable) (Eytan) (SAF Handbook).

In addition, synthetic SAF can also be produced from direct carbon capture. It can be produced by capturing CO₂ emissions from industrial processes or directly from the atmosphere. This captured CO₂ is then used as a feedstock in the production of synthetic fuels. Synthetic SAF is a good solution to solve the feedstock supply constraint, as it does not rely on feedstock supply such as non-food crops or waste resources (How all Sustainable) (RSB). However, synthetic SAF technology is still in its early stage of development.

The technology to produce synthetic SAF fuel is called Power to Liquid (PtL). Renewable hydrogen is synthesized with carbon to create methane, which can turn into liquid e-fuel via PtL technology (What is eSAF?) (Niels). Synthetic SAF is carbon neutral, as when it burns, it only emits the carbon captured during the production. As there is theoretically no supply limitation for hydrogen, PtL will likely make up a large proportion of SAF production in the long term once the technology matures (How all Sustainable). It is a promising technology in terms of scalability and sustainability, with the potential to reduce lifecycle emissions by up to 90% (Joe) (Kyle), making it a viable option to achieve the net-zero emission target. Any future breakthrough in power-to-liquid technology will take sustainable aviation fuel to a scalable and cost-effective stage (Campbell).

2. High production cost

The second challenge relates to the cost of SAF production that limits production volume. Depending on the type of SAF, it is typically two to eight times more expensive than traditional jet fuel (Brendan). For synthetic fuel, the cost could be up to eight times with the PtL pathway, as the technology is still in its nascent state of development (Brendan). The high production cost was due to the expensive feedstocks in the case of hydrogen, the high cost of refining fuel from wastes to SAF, the capital intensity required for advanced technologies, and the dedicated infrastructure required for feedstock collection, processing, and distribution (The Price)

(Brendan) (Li). With such a high cost, there is no strong incentive for fuel producers to invest and airlines to purchase these expensive SAFs, as traditional jet fuel accounts for 20-30% of an airline's operational cost (Riefer). If airlines replace 10% of traditional jet fuel with SAF in 2030, the airlines would have to pass an increase in total cost of 4-6% to their customers (Riefer).

Potential solutions

Governments have stepped in to provide subsidies to lower the cost and offer incentives to encourage fuel producers to increase production. This includes governments legislating policy support and striving for long-term agreements amongst aviation industry stakeholders to provide demand clarity to fuel producers. For example, since the passage of the Inflation Reduction Act (IRA) in the United States in 2022 and ReFuelEU in Europe in 2023, the global demand for SAF based on announced airline offtake agreements has almost doubled from 2022 to 2025 (Campbell). By setting up SAF offtake agreements, buyers agree to buy a certain amount of SAF from the producers at a fixed price over a specific period of time. This scheme provides certainty on price and demand, and encourages fuel producers to allocate more resources to SAF rather than diesel production that has been the focus in recent decades (Campbell) (Li) (Scaling Up Sustainable). In Europe, the ReFuelEU Aviation aims to mandate a gradual increase in SAF blending with conventional fuels, starting at 2% in 2025 and reaching 70% by 2050 (Bastin). Such mandates create a guaranteed market for SAF, encouraging investment and innovation.

Governments also introduced tax credits for SAF to incentivize production, while on the demand side, the tax credits encouraged purchases (Campbell). Most existing tax incentives have expiry dates. A longer-term incentive program can provide more clarity and confidence for industry stakeholders to scale up their demand as well as supply of SAF. In addition, the EU launched the Emission Trading System (ETS) Directive that requires airlines to pay for their greenhouse gas (GHG) emissions, and this can incentivize airlines to use SAF and other green fuel alternatives (Scaling Up Sustainable) (Bastin). Other financial incentives include subsidies to fuel producers to reduce their financial burden (Scaling Up Sustainable) (Wen). All the schemes discussed can increase the demand and supply of SAF, thus helping to lower the cost of production through economies of scale (Paul).

Another driver for the higher production cost is that SAF production facilities are concentrated in specific regions, requiring transport systems to move feedstocks to production sites and fuel to aviation hubs (Hargreaves). To mitigate this, research is being conducted to decentralise the production networks that allow SAF facilities to be closer to the sources of feedstocks. This proximity can reduce the transportation costs associated with moving raw materials to refineries. The cost savings can be significant, especially for remote locations or smaller operations, which can contribute to a lower cost of production (Andreas). Decentralized SAF production facilities can also be established at or near airports, allowing for on-site fuel generation. This setup is particularly beneficial for remote airports where transportation distances to refineries are long, thus reducing the need for extensive transportation logistics and associated costs (Andreas). Integrating SAF into existing jet fuel supply chains can minimize the need for

separate infrastructure and transport, allowing producers to benefit from economies of scale and lowering the overall production cost (Beunis).

3. Limited production capacity

The other challenge relates to the limited production capacity. According to industry estimates, current SAF production capacity is only a small fraction of what is needed to meet the IATA goal of 10% SAF usage by 2030 (Committed to 10%). SAF production doubled between 2022 and 2023, but it only covered 0.53% of aviation fuel needs (Beresnevičius). Rapid deployment of production capacities is critical in scaling up SAF commercially to meet global demand, as the current pipeline of projects only covers around one-third of the estimated demand in 2030 (Scaling Up Sustainable). Scaling up SAF production would require significant investments to build refineries and associated infrastructure.

Potential solutions

At the moment, governments and industry stakeholders are making efforts to increase production capacity. For example, the US Department of Energy has approved a loan of \$1.67bn in January 2025 to Montana Renewables to expand the renewable fuel facilities in Montana. This expansion aims to increase SAF production capacity from 140 million gallons per year to 315 million gallons per year. Once fully operational, this facility is expected to produce about 12% of global SAF by 2030 (\$1.67 Billion). In addition, the SAF Grand Challenge also aims for US production of 3 billion gallons of SAF per year by 2030 and 35 billion gallons of SAF per year by 2050 (\$1.67 Billion). This initiative is supported by substantial investments and regulatory incentives designed to promote the adoption of SAF.

Furthermore, governments can issue green bonds to provide funding for SAF infrastructure projects. The green bond market in the U.S. experienced significant growth in the past decade, with nearly \$51 billion in green bonds issued in recent years (Green bonds).

This trend reflects increasing interest from both public entities and private investors in financing sustainable projects. Loans with reduced interest costs to fund SAF projects should also be encouraged (Eytan). Given that it is capital intensive to build the infrastructure, it is critical for the financial sector to invest in SAF-related projects to support large scale developments (Campbell). Airlines can work with the financial sponsors to co-invest and to fund technology development and production facilities for the large-scale roll-out of SAF (Campbell).

Another way to increase SAF production capacity is to convert existing renewable diesel plants into SAF production facilities. Like other sectors, such as motor vehicles, have been significantly more advanced in using alternative energy sources. Manufacturers and consumers have adopted the use of electricity and batteries to power electric vehicles. The success of electric power for automobiles will free up production capacity and feedstocks for the aviation sector to increase SAF production commercially to meet the aviation demand (How all Sustainable) (Campbell). There are emerging efforts to leverage existing renewable diesel infrastructure to produce SAF. The conversion of renewable diesel facilities to SAF facilities will

increase production capacity in a more time and cost efficient manner (Maria). Governments should provide financial incentives to owners of diesel facilities for such conversions. As ground vehicles move towards electrification, more production facilities and resources should be reallocated to the aviation industry.

4. Lack of SAF standardized frameworks

Last but not least, regulations and standardization are important factors that will determine the success of SAF adoption. For instance, different regulatory frameworks across jurisdictions can complicate SAF production. Specifically, the European Union has implemented mandates for SAF usage (Brendan). Its regulatory framework is one of the most developed. In the EU, aviation biofuels defined under ReFuelEU Aviation are produced from biomass with exclusions from food and feed crops which are not considered sustainable sources of feedstock. In the US, SAF is mainly produced by converting cellulosic waste into ethanol and then into jet fuel. The SAF produced from biomass may not necessarily meet the definition under ReFuelEU Aviation in the EU (Brendan). In addition, the uncertainty around US federal and state incentive policies can slow down the production and adoption of SAF (Kerouredan). In other regions like ASEAN, there is a lack of clear policy guidance and incentives on SAF production (Hong). Even though palm oil is widely available in ASEAN countries, there are environmental concerns and debates on the use of palm oil as possible feedstock due to deforestation and changes in land usage (Hong). Thus the lack of harmonization can create hurdles, limiting the potential for global production and adoption of SAF (Brendan).

Potential solution

Globalisation of SAF standards is necessary to ensure quality, sustainability, and compatibility with existing aircraft and infrastructure. They can also facilitate the production and distribution of SAF around the globe (Eytan) (Scaling Up Sustainable). Developing reliable and internationally recognised standards can facilitate the global use of SAF (Eytan). Organizations such as the International Civil Aviation Organization (ICAO), the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), and the International Air Transport Association (IATA) could play a pivotal role in leading these standardization efforts (Brendan) (Taylor). They can set up harmonised policies across countries to facilitate the production, distribution, and deployment of SAF globally (Developing Sustainable)

Conclusion

Sustainable Aviation Fuels (SAFs) offer an effective solution for decarbonizing aviation, leveraging their full compatibility with the existing aircraft to drive toward net-zero carbon emissions by 2050. However, widespread adoption of SAF faces significant hurdles, including constrained feedstock availability, elevated production cost, limited scalability, and the absence of global standardized frameworks. These challenges, while formidable, can be overcome through coordinated efforts among policymakers, industry leaders, and researchers. By

implementing robust policies such as fuel blending mandates and carbon pricing, investing in innovative production technologies, and fostering global collaboration, the aviation sector can scale SAF production to achieve commercial and economic viability. Such collective action is imperative to position SAFs as a cornerstone of sustainable aviation, enabling the industry to meet climate goals by 2050.

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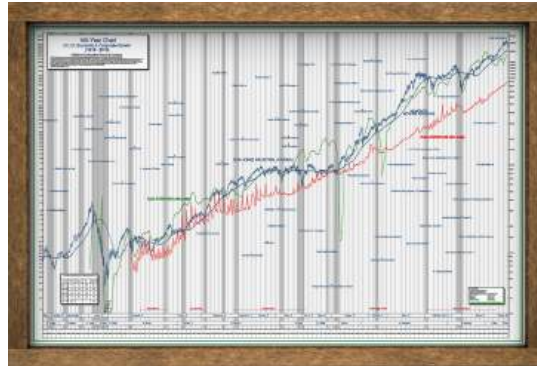
AI Stock Market Algorithm By Arav Choudhary

Abstract

Predicting stock price movements is challenging due to the market's complexity and sensitivity to realtime events. Traditional methods often rely on historical data alone, overlooking the impact of financial news on market sentiment. This study combines historical stock prices with realtime headlines to test whether artificial intelligence (AI) can improve stock prediction accuracy. Machine learning models including linear regression, decision trees, random forests, and neural networks were trained to forecast the next day's opening prices using the previous three days of data. Performance was evaluated using mean squared error (MSE) across companies such as Google, Tesla, Apple, and Nike, followed by a trading simulation to test profitability with different starting capital levels. Results show that neural networks and tuned random forests achieved lower MSE values and higher simulated profits than simpler models, suggesting AI driven systems can enhance stock prediction and support automated trading strategies.

Introduction

One of the biggest challenges in the world of finance is figuring out how to accurately predict stock movements. While traditional stock analysis methods mostly focus on historical prices, they often miss the impact of real time news. News can heavily influence market sentiment, causing price shifts that historical data alone can't account for. The stock market itself is incredibly complicated. There are hundreds of factors at play at any given time which makes it tough to build models that can reliably predict what's going to happen next.



That's why this project was built around the idea of using artificial intelligence to blend two different kinds of data: historical stock prices and real time financial news. The thinking here is that by combining these two sources, the model can get a clearer picture of what's really driving price changes. The goal is to build a system that doesn't just rely on numbers but also understands the mood and movement of the market based on what's happening in the news.

The end result being aimed for is a model powered by AI that can analyze both historical data and current financial headlines to make accurate predictions about where stock prices are

headed. This kind of system would give investors a smarter, more reliable way to decide what to invest in especially in a market that tends to be unpredictable and fast moving. It's designed for anyone looking to make decisions based on real insights rather than instincts.

Stock prices are critical in finance because they help everyone from everyday investors to massive firms decide when to buy or sell. But the market isn't driven by logic alone. Economic reports, company announcements, interest rate changes, and international events all play a role in what happens day to day. With so many moving pieces, it's hard to see what's coming. But if there were a way to predict those movements better, it could help minimize risks, guide smarter investments, and improve overall returns. That's good news for everyone involved.

This raises an important question: Can artificial intelligence, especially machine learning, actually make stock price predictions better? AI is known for handling large, messy data sets and spotting patterns that aren't obvious to the human eye. This project explores how well machine learning models can learn from past market behavior and apply that knowledge to predict where stock prices might go. The goal is to see if AI can catch things that traditional methods would miss.

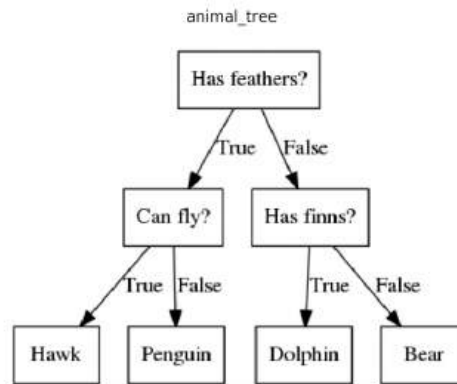
If it works, the benefits are huge. Accurate forecasts can help investors know when to make their moves, reducing guesswork and helping them manage their portfolios with more confidence. Over time, AI could even power trading systems that don't need constant human input. These systems could act quickly as the market changes, which might lead to more consistent performance and open up opportunities that investors wouldn't otherwise see.

To understand why AI is being used for this, it's helpful to look at how the stock market has evolved. It goes all the way back to the 1600s with the founding of the Amsterdam Stock Exchange, and later in 1792, the New York Stock Exchange came onto the scene. Since then, the market has gone through major events like the Great Depression, the dot com bubble, and the 2008 financial meltdown. Each of these shows how the market is influenced not just by numbers, but by politics, wars, and economic changes too. Looking back at these events helps models understand how similar patterns might unfold in the future.

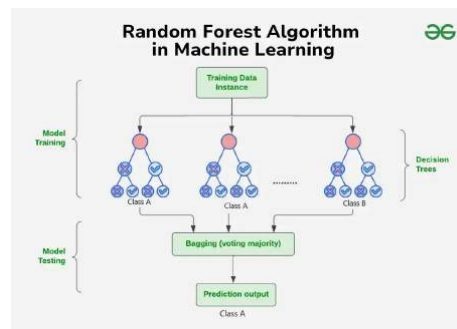
Even though the market has delivered long term returns of about 7 to 10 percent per year, short term price movements are much harder to predict. Things like breaking news, political decisions, or even viral tweets can move the market in minutes. That's where AI really shines. It can process all this incoming information at once and figure out what might happen next. With that kind of processing power, investors get better tools to manage risk and make smarter choices.

Material and Methods

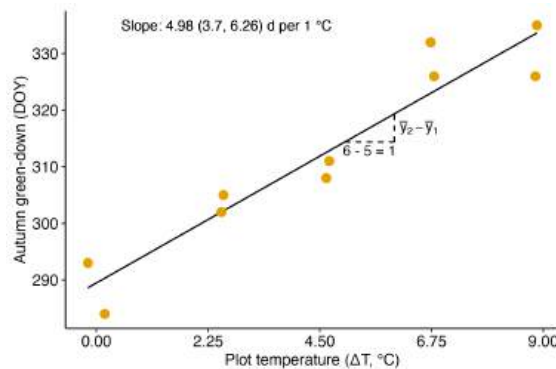
To actually build the model, several types of machine learning algorithms were used. We gave each model the last three open prices of a certain stock, and our target is to predict the next open price of said stock. One of them was the decision tree, a model that breaks data into branches to make decisions. Each decision point, or node, leads to different outcomes depending on the input data. These are simple to understand but can lead to overfitting if the tree gets too deep. That's why tuning its depth is a key step.



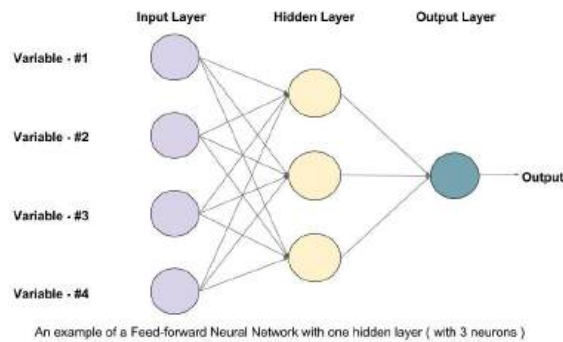
To add more accuracy and reduce overfitting, random forests were introduced. These models are made up of many decision trees, and they average all their predictions to get more reliable results. They're not as easy to explain as single trees, but they do a better job of handling outliers and complicated data. Key settings here include how many trees are used and how deep each one is allowed to grow.



Linear regression was also tested. It's one of the simplest models out there; it draws a straight line to show the relationship between variables. It's fast and easy to use but only works when the relationship between inputs and outputs is linear. Its main settings include the learning rate and alpha value.



Then there's the neural network, a model inspired by the human brain. These models use layers of connected "neurons" that pass information through one another. They're great at capturing complex, non linear relationships in data. The number of hidden layers and training epochs are two important parts that need to be adjusted to get good results.



Once the models were ready, a basic simulation was run using linear regression. The code started by predicting future stock prices and setting a few key variables: k , which stands for how many stocks to trade at once; money, the starting cash; and stocks, which began with k units. The loop ran for 1,200 steps, simulating around five years of trading. At each step, it compared the next day's predicted price with today's actual price. If the forecasted price was higher and there was enough cash, it bought k stocks. If the price was expected to drop and the user owned enough shares, it sold k .

This simple set of rules made sure the simulation didn't try to buy stocks without money or sell stocks that weren't owned. At the very end, the script checked if any stocks were still in the portfolio and sold them at the last known price to close everything out. This step was important without it, leftover stocks wouldn't count toward the final result. After that, it printed out how much money was left and confirmed that all stocks were sold. This gave a clear snapshot of how well the model performed across the entire time period.

This simulation was a simplified way to test whether the model's predictions could actually generate profit. It ignored real world complications like fees or slippage, focusing only on whether the model's signals would lead to growth. Using fixed trade sizes and basic rules kept things easy to understand while still offering useful insight. In the end, this made it easier to evaluate whether the model's forecasts could actually be used in an automated trading system.

To train the model properly and still get a fair evaluation of its accuracy, the dataset was split into two parts. About 67 percent of the data was used to train the model, while the remaining 33 percent was set aside for testing. This allowed the model to learn from most of the data while still being tested on information it hadn't seen before giving a realistic view of how it might perform in the real world.

During the project, some models showed signs of overfitting, meaning they performed very well on training data but not as well on new, unseen data. This happened mainly with deeper

decision trees and larger random forests when predicting stocks like Tesla and Apple. To reduce overfitting, the depth of decision trees was limited, and the number of trees in random forests was tuned. Neural networks were also monitored to make sure they did not memorize the training data by adjusting the number of layers and training iterations. These steps helped the models generalize better to new stock data.

In other attempts to avoid overfitting, various techniques can be used. One of these is dropout, that is, randomly disables a group of neurons in the course of training in order to ensure that the model is not over dependent upon any one particular set of connections. One other method is regularization, which imposes a loss on the model of having very large weights, to promote it to retain simpler, more general predictions. These techniques can aid in getting the model to perform well when working on new stock data that the model has never seen, rather than memorizing the training data.

Results

The models were tested on four companies: Google, Tesla, Apple, and Nike. Each model was trained on 67 percent of the data and tested on the remaining 33 percent. The performance was measured using Mean Squared Error, or MSE. A lower MSE means better predictions.

For the test set, the results for Google were as follows. The linear regression model achieved an MSE of 12.17. The decision tree with a maximum depth of 5 achieved 9.79. The random forest with a maximum depth of 2 and 100 trees had a much higher error at 156.12. The neural network with 2000 training iterations had the lowest error at 7.3. A smaller decision tree with a maximum depth of 3 had 38.79, while a random forest with a maximum depth of 4 and 150 trees achieved 8.45. A second neural network with 2570 iterations also had 7.3, matching the best score.

For Tesla, the linear regression model scored 103.9, the decision tree with depth 5 scored 148.21, and the random forest with depth 2 scored 798.5. The neural network scored 104.07, while the smaller decision tree scored 472.83. The tuned random forest with depth 4 scored 132.19, and the second neural network scored 104.07, again similar to the first.

For Apple, the linear model scored 9.42, the larger decision tree scored 16.78, and the first random forest scored 219.67. The first neural network scored 10.66, the smaller decision tree scored 41.78, the tuned random forest scored 12.21, and the second neural network again scored 10.66.

Finally, for Nike, the linear model scored 4.93, the larger decision tree scored 7.1, the first random forest scored 114.17, the first neural network scored 5.89, the smaller decision tree scored 30.81, the tuned random forest scored 8.36, and the second neural network again scored 5.89.

Training errors were similar to the test errors. For example, on Google, the neural network had a training MSE of 7.82 compared to 7.3 on the test set, showing that the model was not overfitting. For Tesla, the neural network had a training MSE of 110.29 compared to 104.07 on the test set. For Apple, it had 11.93 compared to 10.66, and for Nike, 5.51 compared to 5.89.

A trading simulation was also run using the models' predictions. Starting with ten thousand dollars and trading five stocks at a time, Google ended with 19,775 dollars, Amazon ended with 15,965, Apple with 20,983, Nike with 10,444, Tesla with 80,823, Nvidia with 102,892, McDonalds with 19,825, and Chipotle with 19,775.

With fifteen thousand dollars starting capital and the same five stock trading rule, Google ended with 30,773 dollars, Amazon with 22,236, Apple with 30,199, Nike with 14,101, Tesla with 128,807, Nvidia with 144,410, McDonalds with 29,871, and Chipotle with 30,773.

Starting with twenty thousand dollars, Google ended with 41,079 dollars, Amazon with 29,297, Apple with 39,893, Nike with 17,495, Tesla with 170,401, Nvidia with 176,668, McDonalds with 28,532, and Chipotle with 41,079.

Finally, starting with twenty five thousand dollars, Google ended with 51,149 dollars, Amazon with 36,654, Apple with 50,321, Nike with 20,796, Tesla with 185,275, Nvidia with 204,128, McDonalds with 45,720, and Chipotle with 51,149.

The same simulations were run for three stock trades. Starting with ten thousand dollars, Google ended with 20,551 dollars, Amazon with 14,698, Apple with 19,906, Nike with 9,136, Tesla with 91,781, Nvidia with 93,494, McDonalds with 19,605, and Chipotle with 20,551.

With fifteen thousand dollars starting capital, Google ended with 30,689 dollars, Amazon with 21,992, Apple with 30,193, Nike with 12,477, Tesla with 111,165, Nvidia with 122,477, McDonalds with 27,432, and Chipotle with 30,689.

With twenty thousand dollars starting capital, Google ended with 40,045 dollars, Amazon with 28,474, Apple with 40,279, Nike with 15,752, Tesla with 134,602, Nvidia with 159,435, McDonalds with 34,663, and Chipotle with 40,045.

Finally, with twenty five thousand dollars starting capital, Google ended with 47,586 dollars, Amazon with 35,068, Apple with 48,348, Nike with 19,234, Tesla with 158,235, Nvidia with 197,023, McDonalds with 41,413, and Chipotle with 47,586.

Across almost all scenarios, Tesla and Nvidia produced the highest final amounts, showing that the model's signals worked especially well for these companies.

Testing MSE for each

	Linear Model	Decision Tree (Max Depth: 5)	Random Forest (Max Depth: 2, n_estimators=100)	Neural Network (max_iter=2000)	Decision Tree (Max Depth: 3)	Random Forest (Max Depth: 4, n_estimators=150)	Neural Network (max_iter=2570)		
Google	12.17	9.79	156.12	7.30	38.79	8.45	7.30		
Tesla	103.90	148.21	798.50	104.07	472.83	132.19	104.07		

Apple	9.42	16.78	219.67	10.66	41.78	12.21	10.66		
Nike	4.93	7.10	114.17	5.89	30.81	8.36	5.89		

Training MSE for each

	Linear Model	Decision Tree (Max Depth: 5)	Random Forest (Max Depth: 2, n_estimators=100)	Neural Network (max_iter=2000)	Decision Tree (Max Depth: 3)	Random Forest (Max Depth: 4, n_estimators=150)	Neural Network (max_iter=2570)		
Google	6.94	6.59	83.67	7.82	31.55	7.02	7.82		
Tesla	106.56	91.05	535.39	110.29	281.08	101.38	110.29		
Apple	10.62	10.03	120.11	11.93	42.66	10.87	11.93		
Nike	4.95	5.37	66.65	5.51	25.66	6.27	5.51		

Write Final Amount based on different starting values (5 stocks)

	Google	Amazon	Apple	Nike	Tesla	Nvidia	McDonalds	Chipotle	
10000	19775	15965	20983	10444	80823	102892	19825	19775	
15000	30773	22236	30199	14101	128807	144410	29871	30773	
20000	41079	29297	39893	17495	170401	176668	28532	41079	
25000	51149	36654	50321	20796	185275	204128	45720	51149	

Write Final Amount based on different starting values (3 stocks)

	Google	Amazon	Apple	Nike	Tesla	Nvidia	McDonalds	Chipotle	
10000	20551	14698	19906	9136	91781	93494	19605	20551	

15000	30689	21992	30193	12477	111165	122477	27432	30689	
20000	40045	28474	40279	15752	134602	159435	34663	40045	
25000	47586	35068	48348	19234	158235	197023	41413	47586	

Discussion

The results show that neural networks and tuned random forests performed best in predicting stock prices. Neural networks achieved the lowest MSE across almost all companies, especially for Google and Apple. Simpler models like linear regression performed reasonably well on some stocks but could not capture complex patterns as effectively.

The trading simulations further proved that better predictions led to higher profits. For instance, with \$15,000 starting capital, Tesla's portfolio grew to \$128,807 using 5 stock trading. This shows that even a simple trading rule using predictions from these models can significantly outperform the starting capital.

However, the results also highlight some limitations:

- Tesla's stock was much harder to predict, with high MSE across all models.
- Real trading involves fees, slippage, and risk controls, which were not included here.
- Using only three previous days as input may limit long term trend detection.

Still, the findings suggest that combining machine learning with financial data can produce meaningful improvements over naive methods. Future work will integrate sentiment analysis from real time headlines to capture market mood in addition to price patterns.

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- Random Forest Regressor in scikit-learn:
<https://scikit-learn.org/stable/modules/ensemble.html#random-forests>
- Multi-layer Perceptron Regressor (MLPRegressor) in scikit-learn:
https://scikit-learn.org/stable/modules/generated/sklearn.neural_network.MLPRegressor.html

Advancements in Nanoparticle-Based Drug Delivery Systems for Breast Cancer Treatment

By Pearl Lakhani

ABSTRACT

Breast cancer remains one of the most commonly diagnosed cancers among women in the United States, with more than 310,720 cases being diagnosed in 2024. Though there are developments in breast cancer detection and treatment, breast cancer still remains to be a significant issue. Traditional treatment options such as chemotherapy and hormone therapy often result in severe side effects, drug resistance, and poor selectivity making it difficult to remove tumors without harming healthy tissue. However, nanoparticles offer promising treatment options due to their ability to encapsulate drugs and deliver drugs directly to tumor sites which lowers systemic toxicity and improves treatment precision. In breast cancer treatments, nanoparticles are engineered for passive and active targeting, using mechanisms like the Enhanced Permeability and Retention (EPR) effect or ligand-receptor binding to release chemotherapy drugs in a controlled and tumor site specific manner. Clinically, formulations like nab-paclitaxel and pegylated liposomal doxorubicin have demonstrated improved outcomes and reduced side effects compared to other traditional treatments. As research progresses, the development of multifunctional and specific nanoparticles may lead to a new era of precision medicine in breast cancer treatment. By improving both efficacy and safety, nanoparticle-based treatments show a significant advancement in the ongoing effort to overcome the obstacles of current cancer treatments.

INTRODUCTION

In 2024, more than 310,720 cases of invasive breast cancer are projected in women. In 2022 alone, 42,211 women in the United States died from the disease, making it the most common cancer affecting women (*American Cancer Society*). Breast cancer develops when cells grow and divide uncontrollably, forming tumors that often begin in the milk ducts or lobules, which produce and transport milk (*American Cancer Society*).

Breast cancers are classified based on molecular and genetic characteristics. Hormone receptor (HR)-positive cancers grow in response to estrogen (ER-positive) or progesterone (PR-positive), while HR-negative cancers lack these receptors. Another subtype, HER2-positive breast cancer, results from overexpression of the HER2 gene, leading to aggressive tumor growth (*National Cancer Institute*). The most common subtype is hormone receptor-positive (HR+). These cancers grow more slowly and generally are more responsive to hormone-blocking therapies such as tamoxifen or aromatase inhibitors, which are used to target estrogen-driven signaling pathways (*BreastCancer.org*). However, they may recur years after initial treatment, requiring long-term monitoring (*National Cancer Institute*).

HER2-positive breast cancers result from overexpression of the HER2 (human epidermal growth factor receptor 2) gene, which leads to an abundance of the HER2 protein on tumor cell surfaces. This abundance leads to aggressive tumor growth and spread but also creates a

therapeutic target. Drugs such as trastuzumab (Herceptin) and pertuzumab specifically block HER2 signaling, which improves survival for patients with this subtype (*National Cancer Institute*). HR+ and HER2 cancers together account for 68% of cases between 2015–2019 (*North American Association of Central Cancer Registries*).

Conversely, triple-negative breast cancer (TNBC) lacks the ER, PR, and HER2 receptors, which makes it unresponsive to both hormone therapy and HER2-targeted drugs (*National Cancer Institute*). TNBC is often more aggressive, more likely to recur, and disproportionately affects younger women and women of African or Hispanic descent (*American Cancer Society*). Due to the fact that TNBC lacks druggable receptors, it is mostly treated with chemotherapy; however, newer approaches such as immunotherapy and nanoparticle-based delivery are being experimented with (Ibrahim and Desai). TNBC represents 10% of cases in the U.S. but 20% worldwide (*BreastCancer.org*). Figure 1 illustrates the distribution of these subtypes in the U.S. from 2015–2019 (*North American Association of Central Cancer Registries*).

Other less common subtypes also exist, including luminal A and luminal B (both HR+ but differing in growth rate and HER2 status) and basal-like cancers, which have significant overlap with TNBC and are characterized by rapid growth and poor prognosis (*National Cancer Institute*). Overall, these classifications show the biological diversity of breast cancer and highlight the need for targeted therapies that can adapt to each tumor’s unique molecular profile.

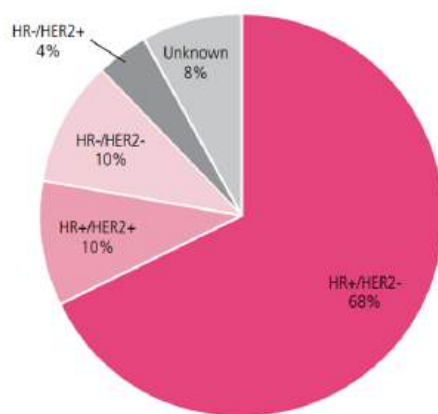


Figure 1: Distribution of breast cancer subtypes in the United States, 2013–2019: HR+/HER2- (68%), HR+/HER2+ (10%), HR-/HER2- (10%), HR-/HER2+ (4%), and unknown (8%). FDG PET/CT & Breast Cancer - Northern California PET Imaging Center.” *Northern California PET Imaging Center*, 19 Sept. 2023, ncpic.org/breast-cancer/. Accessed 27 Sept. 2025.

Diagnosis typically involves imaging methods such as mammography, ultrasound, and MRI, alongside biopsies and biomarker testing for ER, PR, and HER2 (*National Cancer Institute*). While advances in surgery, chemotherapy, and radiation have improved outcomes, challenges persist. Chemotherapy, for example, affects both cancerous and healthy cells, causing systemic toxicity, nerve damage, and blood changes (*American Cancer Society*). Hormone therapy increases risks of other cancers and can impair fertility (*American Cancer Society*). These

limitations underscore the urgent need for safer, more selective treatments—an area where nanotechnology has shown significant promise (Ibrahim and Desai; Yagublu et al.). Figure 2 illustrates the key physicochemical properties of nanoparticles that enable them to act as targeted drug delivery systems in cancer therapy. This paper explores the role of nanoparticle-based drug delivery systems in breast cancer, with a focus on their mechanisms, clinical applications, and potential to overcome the shortcomings of conventional therapies.

NANOPARTICLES BACKGROUND

Nanotechnology was first introduced in 1959 by Nobel laureate Richard P. Feynman, who envisioned the manipulation of matter at the atomic and molecular scale (Feynman). This innovation enables the creation of materials, such as nanoparticles (NPs), at a nanometer scale. NPs are typically between 1 and 100 nanometers in size. Their size, shape, and surface area give them many applications, from imaging to drug delivery. NPs typically consist of a core, a chemically distinct shell, and an outer layer with molecules or polymers (Misiak et al.).

NPs can be categorized by their material type. For example, some include metallic, metal oxide, carbon-based, or lipid nanoparticles, and their properties affect how they are used in medicine. Liposomes are lipid-based and are often used to carry chemotherapy drugs such as doxorubicin. Their phospholipid bilayers mimic cell membranes, allowing them to fuse more efficiently with target cells while reducing harm to healthy cells. This encapsulation reduces systemic toxicity (Barenholz). Metallic nanoparticles such as gold or platinum are widely used in imaging and photothermal therapy because of their ability to convert light into heat (Huang et al.). Additionally, dendrimers are highly branched synthetic polymers that provide precise control over size and surface functionality, making them efficient for targeted drug delivery and gene therapy in breast cancer (Kesharwani et al.). These unique characteristics allow NPs to bypass biological barriers, enhance drug solubility, and precisely target disease sites, unlike conventional drug molecules. However, challenges remain in transferring these benefits to clinical settings, including ensuring long-term biocompatibility, avoiding immune responses, and achieving consistent drug release in complex biological environments (Bhushan). Each of these nanoparticle types offers unique physical and chemical properties that make them well-suited for specific therapeutic strategies, including drug delivery, imaging, and hyperthermia. Figure 2 illustrates the key characteristics of nanoparticles that enable their biomedical applications.

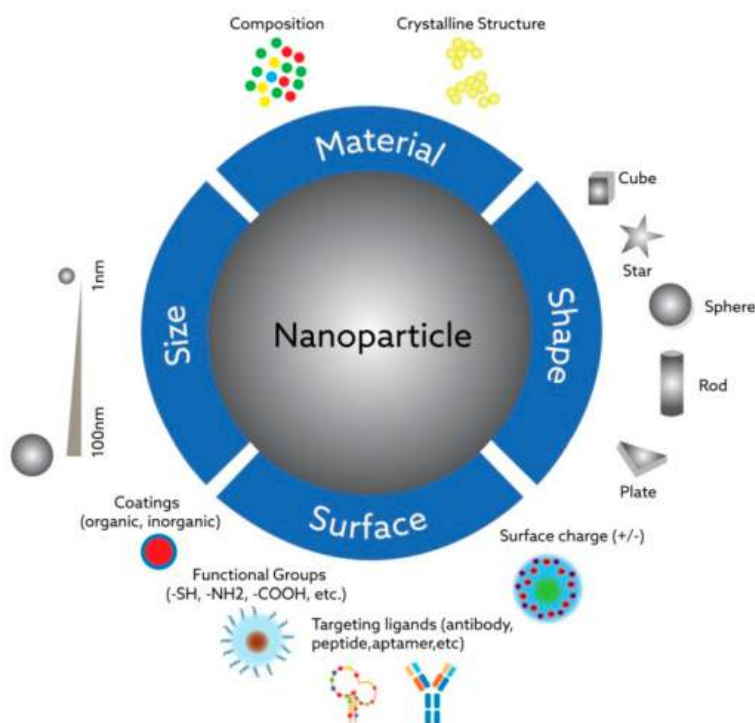


Figure 2: Key characteristics of nanoparticles, including material (composition, crystalline structure), shape (cube, star, sphere, rod, plate), size (1 nm–100 nm), and surface properties (coatings, functional groups, targeting ligands, and surface charge). Yagublu, Vugar, et al. “Overview of Physicochemical Properties of Nanoparticles as Drug Carriers for Targeted Cancer Therapy.” *Journal of Functional Biomaterials*, vol. 13, no. 4, 20 Oct. 2022, p. 196, www.ncbi.nlm.nih.gov/pmc/articles/PMC9590029/, <https://doi.org/10.3390/jfb13040196>. Accessed 13 Sept. 2025.

NPs are produced using either top-down or bottom-up methods. The top-down approach involves breaking down bulk materials, for example, through mechanical milling or laser ablation. In contrast, the bottom-up approach builds particles atom by atom or molecule by molecule using techniques like Chemical Vapor Deposition (CVD), which forms nanoparticles by reacting gaseous precursors on a heated substrate, or the Sol-Gel Process, which involves transitioning a solution into a solid gel phase to create uniform nanoparticles (Misiak et al.). These methods affect many factors such as the structure, biocompatibility, and application of NPs in medicine. Top-down methods are generally easier to scale up and rely on bulk processing, which often makes them less expensive because those techniques are already common in the industry. However, they may result in less uniform particle sizes. Bottom-up approaches are capable of producing highly uniform and customizable nanoparticles with precise control, but are often more expensive and complex. This limits scalability, due to the need for specialized equipment and controlled conditions.

The chosen production method also has significant implications for the scalability and cost-effectiveness of nanoparticle synthesis—critical factors for their eventual clinical translation. While promising, the design of effective nanoparticles also requires careful consideration of their

biocompatibility and potential toxicity within biological systems, necessitating rigorous research into material selection and surface modifications to ensure safe and targeted use in humans (Singh and Lillard).

NANOPARTICLES IN CANCER

NPs are especially useful in drug delivery, particularly in cancer therapy. Their ability to encapsulate or coat drugs protects them from degradation in the bloodstream and allows for controlled release at the tumor site. Drugs can be inserted into nanoparticles by physical entrapment, chemical conjugation, or absorption onto the surface (Torchilin). After delivery to the tumor, release mechanisms such as diffusion, degradation of the nanoparticle material, or other external triggers ensure that the drug is delivered in a controlled and site-specific manner. Two major tumor-targeting mechanisms include passive targeting and active targeting. Passive targeting is based on the Enhanced Permeability and Retention (EPR) effect. Because tumor vasculature is often leaky, with gaps ranging from 100 to 800 nm between endothelial cells, nanoparticles are able to pass through more easily than in normal tissues. In addition, tumors have poor lymphatic drainage, which causes nanoparticles to accumulate at the tumor site over time (Maeda et al.).

Active targeting uses antibodies, peptides, or small molecules (ligands) that bind to specific receptors overexpressed on cancer cells. A common example includes folic acid (ligand) binding to folate receptors, which are often overexpressed in breast and other cancer cells (Lu and Low). This receptor-mediated targeting helps direct the nanoparticle to the cancer site, improving treatment precision and minimizing harm to healthy tissues.

Stimuli-responsive NPs further improve precision by releasing drugs in response to pH, temperature, or enzymes unique to cancer cells. For example, many tumors have a lower pH level than normal tissues; therefore, pH-sensitive nanoparticles can be designed to release drugs into specific environments based on acidity. Enzyme-sensitive systems can respond to enzymes like matrix metalloproteinases (MMPs), which are abundant in tumor microenvironments (Rosenblum et al.). These smart-release mechanisms are beneficial for targeting by ensuring drugs are only released once the nanoparticle reaches the tumor. This reduces side effects and increases treatment efficacy, which is an essential goal of modern breast cancer therapy.

Nab-paclitaxel (*Abraxane*) is an albumin-bound formulation of paclitaxel, a chemotherapy drug that works by interfering with the microtubules involved in cell division, preventing cancer cell replication. Unlike conventional paclitaxel, it does not require toxic solvents. Its nanoparticles use the albumin protein to enter tumors by binding to cell surface proteins (such as gp60) that aid in transcytosis, and to tumor-expressed proteins like SPARC, which help retain albumin in the tumor environment, enhancing drug delivery and reducing side effects (Untch et al.). A Phase III clinical trial showed that nab-paclitaxel had a 38% pathological complete response (pCR) rate compared to 29% for conventional paclitaxel in high-risk HR-positive/HER2-negative breast cancer (Untch et al.). Another study found that a 3-week schedule was more effective than a 4-week one for HER2-negative metastatic breast cancer

(Gradishar et al.). This is vital because it shows that adjusting intervals of dosing for nanoparticle-based therapies like nab-paclitaxel can improve treatment outcomes, helping to maximize therapeutic benefits while maintaining patient safety. However, challenges remain, such as cost and variability in how efficiently albumin binds between different patients, which can impact treatment outcomes.

Liposomes, like Pegylated Liposomal Doxorubicin (PLD), increase drug circulation and reduce toxicity. PEG (polyethylene glycol) coating increases circulation time by shielding the nanoparticle from the immune system, which in turn enhances drug accumulation in tumors. The PELICAN Phase III trial found PLD comparable to capecitabine in efficacy but with fewer adverse events (Vici et al., “Phase III”). A Phase II study combining PLD and gemcitabine yielded a median overall survival of 16.1 months, with 78% of patients benefiting from the treatment (Vici et al., “Phase II”). Though they have success in reducing toxicity, challenges such as achieving consistent tumor penetration for larger-sized liposomes still remain. These challenges are leading to more research in smaller and more deformable liposomal formulations. Polymer nanoparticles from biodegradable materials have also shown promise. In one study, doxorubicin-loaded polymeric NPs showed strong cytotoxic effects against estrogen-dependent MCF-7 breast cancer cells, even at low doses, while maintaining compatibility with healthy cells (Misiak et al.). However, there are difficulties in designing polymers that are both stable in circulation and responsive in tumors, and this remains a barrier to broader clinical use. Inorganic nanoparticles made from metals like platinum enhance cytotoxicity in breast cancer while reducing the side effects associated with traditional platinum-based chemotherapies (Misiak et al.). However, these metal-based NPs can have long-term toxicity and clearance issues, which need to be addressed through cautious material engineering and surface modification.

Other nanoparticle types not discussed in detail here such as dendrimers, viral nanoparticles, and quantum dots are also being actively researched for their potential in breast cancer diagnosis and treatment. Each nanoparticle type has unique advantages in drug loading, imaging, or targeting, but they also have several challenges as well (Rosenblum et al.).

Despite their promise, nanoparticle-based therapies also have limitations. One major obstacle is tumor heterogeneity. Differences in vascularization, receptor expression, and microenvironmental conditions between patients can reduce the consistency of NP delivery. Additionally, resistance has been observed in some cases. For example, breast cancer cells can upregulate drug efflux pumps like P-glycoprotein, which decreases intracellular accumulation of nanoparticle-delivered drugs. This is similar to resistance mechanisms seen with conventional chemotherapies (Patil et al.). Clinical trials have also shown mixed results: while nab-paclitaxel improved pathological complete response rates compared to paclitaxel, other NP formulations such as liposomal cisplatin do not show superior outcomes over their free-drug counterparts in Phase III trials (Boulikas and Pantos). These findings show that while nanoparticles enhance delivery and reduce toxicity, they do not always guarantee improved efficacy. Overall, more research is needed to optimize formulations and overcome resistance mechanisms.

CONCLUSION

Each nanoparticle delivery system has distinct advantages that make it a promising alternative to conventional breast cancer therapies. For example, nab-paclitaxel improves tumor penetration while avoiding solvent-related side effects (Untch et al.). Liposomes such as PLD extend circulation time and lower toxicity while maintaining strong clinical outcomes (Vici et al.). Polymeric nanoparticles offer precision with reduced toxicity, while inorganic nanoparticles can enhance the effectiveness of traditional drugs with fewer side effects (Misiak et al.). Overall, these innovations demonstrate a shift toward more targeted, effective, and safer breast cancer treatments.

These findings are significant for the future of public health. Nanoparticle-based therapies have the potential to reduce the burdens of chemotherapy-related side effects, improve the quality of life for patients, and lower long-term treatment costs by increasing drug efficiency. For future research, the development of multifunctional nanoparticles that combine therapy with real-time imaging could drastically improve both treatment and monitoring. Additionally, tailoring nanoparticles to an individual's tumor biology—or personalized nanomedicine—may redefine precision oncology as a whole.

However, this review also highlights limitations. Much of the current literature relies on preclinical or early-phase clinical studies, meaning there are many unknowns in long-term safety and effectiveness. Some studies may also carry bias, as industry-funded research on nanoparticle formulations often reports more favorable outcomes. Additionally, variability in nanoparticle synthesis methods, patient populations, and study design can make it difficult to directly compare results across trials. These limitations require larger, independent clinical studies, standardized methods of nanoparticle production, and closer evaluations of cost-effectiveness and accessibility. As scientists continue to overcome challenges in biocompatibility, large-scale manufacturing, and regulatory approval, nanoparticle therapies may ultimately redefine the standard of care for breast cancer.

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Machine Learning for Numismatic Classification: Ancient Chinese Coins with Subtle and Bold Designs By Jiacheng Yang

Abstract

Numismatic classification is a cornerstone of archaeological research, offering vital chronological markers for interpreting historical contexts. However, traditional methods often rely on manual expertise, leading to subjective, time-consuming, and inconsistent results. This study evaluates the effectiveness of Convolutional Neural Networks (CNNs), specifically a fine-tuned MobileNet model, in automating the classification of ancient Chinese coins. The findings show that CNNs perform better on coins with pronounced design variations compared to those with minor stylistic differences, particularly under constrained dataset conditions. By examining the relationship between stylistic diversity and CNN performance, this study provides actionable insights for developing comprehensive machine learning-based tools in numismatics.

Key Words

Numismatic Classification; Ancient Chinese Coins; Convolutional Neural Networks (CNNs); MobileNet; Minor Stylistic Differences; Prominent Design Variations; Comprehensive Machine Learning-Based Tools

Introduction

In archaeological excavations, the discovery of ancient coins frequently serves as a reliable and essential method for dating sites and interpreting historical contexts (Casey, 1986; Lockyear, 2007). Coins from different historical periods typically feature distinct designs, inscriptions, and forms influenced by specific political circumstances, economic factors, and resource availability. These distinct characteristics allow archaeologists and numismatists to systematically classify coins, thereby accurately establishing chronological contexts (Grierson, 1975; Metcalf, 2012). Traditionally, coin classification has relied heavily on expert numismatists—a process that, while effective, remains labor-intensive, costly, and subjective, potentially leading to inconsistent or inaccurate outcomes (Kampel & Zaharieva, 2008). Recent advancements in machine learning, particularly the development of Convolutional Neural Networks (CNNs), have opened significant opportunities to automate numismatic classification. Automating this process offers greater objectivity and efficiency to archaeological practices (Anwar et al., 2019; Schlag & Arandjelović, 2017). CNNs have demonstrated exceptional capabilities in classifying Roman coins, which typically feature uniform circular shapes with subtle differences in pictorial and textual details (Anwar et al., 2019). For example, the CNN model CoinNet demonstrated over 98% classification accuracy for Roman Republican coins, indicating CNNs' effectiveness in tasks involving stylistically uniform numismatic artifacts (Anwar et al., 2019). However, the stylistic uniformity seen in Roman coinage does not represent the broad spectrum of numismatic diversity encountered elsewhere, notably within ancient Chinese coins.

China's extensive historical timeline, spanning nearly five thousand years, has produced coins exhibiting both subtle textual variations and significant morphological differences (Hartill, 2005). For instance, coins from the Qing Dynasty, such as the Kangxi Tongbao, display minor inscription differences between various regional mints, whereas coins from the politically fragmented Pre-Qin period exhibit substantial shape variations, including distinct knife-shaped and spade-shaped forms.

Despite this diversity, research on the application of machine learning, particularly CNNs, to automate the classification of Chinese ancient coins remains limited. The only identified study, conducted by Shi (2020), explored the use of neural networks for this purpose but focused exclusively on Kangxi Tongbao coins, which are characterized by their uniform circular shape and subtle textual distinctions (Shi, 2020). This overlaps with prior research by Anwar et al. (2019) on similar types of coins. Additionally, the only existing tool for automating ancient Chinese coin classification was developed by Weipaitang, an e-commerce company. This tool aids users in identifying commonly encountered coin types and estimating their market value, primarily for collection and trade. While it covers coins from nine dynasties and includes 170 types, it is also limited to circular coins with subtle textual variations (Weipaitang, 2014b). This gap leaves CNN performance on ancient coins with significant morphological variations largely unexplored. Irregularly shaped coins, such as those from the Pre-Qin period, represent an important component of ancient Chinese coinage, covering nearly 400 years of history. This highlights the need for a comprehensive model capable of addressing classification tasks for coins with both minor and major stylistic differences. Key questions arise: Will CNN performance on coins with pronounced stylistic differences match, exceed, or fall short of its performance on coins with subtle variations? Furthermore, how might insights from such findings contribute to the development of more comprehensive CNN-based tools for numismatic classification?

Acknowledging these critical research gaps, the present study evaluates CNN performance using Google's Teachable Machine platform, which implements MobileNet—a lightweight CNN architecture recognized for its effectiveness in image recognition tasks (Howard et al., 2017). By fine-tuning MobileNet using two distinct datasets—Kangxi Tongbao coins, characterized by subtle textual distinctions, and Pre-Qin coins, featuring pronounced morphological variations—this study compares their classification accuracy and explores the influence of stylistic diversity on CNN effectiveness. The findings aim to provide practical insights for developing a comprehensive model capable of addressing both minor and major stylistic differences in classification tasks.

Method

To evaluate the classification performance of the CNN-based model on ancient Chinese coins—particularly its effectiveness across coins exhibiting varying stylistic distinctions—this study followed a structured experimental approach, including data collection, dataset preparation, image preprocessing, CNN configuration, training procedures, and performance evaluation.

Relevant Terminology Definitions

To provide clarity and context for the methodologies employed, the following definitions outline key terms and concepts relevant to this study:

- **Machine Learning:** Algorithms that learn patterns from data to improve performance without explicit programming.
- **CNN (Convolutional Neural Network):** A deep learning model that extracts features from visual data, commonly used for image classification.
- **Training and Test Sets:** Data split into two parts—training for learning patterns and testing for evaluating performance on unseen inputs.
- **Generalization:** The ability of a model to apply learned patterns to new data rather than just memorizing the training set.
- **Overfitting:** A model performs well on training data but poorly on test data, indicating it has learned specific patterns instead of generalizable ones.
- **Loss Function:** A calculation measuring prediction errors, guiding the model's optimization to improve accuracy.
- **Learning Rate:** A parameter controlling how much the model's weights adjust during training, balancing speed and stability.
- **Epoch:** A complete pass through the training dataset during the learning process.
- **Batch Size:** The number of samples processed together in one step, impacting training efficiency and stability.

1. Data Collection

The datasets for this research were obtained from the Weipaitang Coin Type Database, managed by the Weipaitang Cultural Entrepreneurship Information Company. Established in 2014, Weipaitang is widely recognized as a leading platform for cultural and collectible artifacts, particularly ancient Chinese coins (Weipaitang, 2014a). This database provides high-quality coin images alongside detailed metadata, including classifications, condition ratings, material compositions, and descriptions of coin variants. These resources formed the foundation for accurate labeling and classification in this study.

2. Dataset Preparation

Two relatively small datasets were compiled to evaluate how the model performs on coins with subtle textual variations and pronounced morphological differences:

- **Kangxi Tongbao Coins:** This dataset consists of 60 images, evenly divided among four subtypes: Baoquan, Baoyuan, Man-Han East, and Man-Han Ji mintmarks. Each subtype is represented by 15 images. The subtle differences in character strokes among these subtypes are challenging to differentiate and are illustrated in Figure 1.

- Pre-Qin Coins:** This dataset contains 60 images, representing four distinct subtypes: knife coins, spade coins, round coins, and ant-nose coins. These coins display significant morphological diversity, making them visually distinct, as shown in Figure 2.

Table 1. Dataset Composition by Subtype and Sample Count

Dataset	Subtypes	Sample Count (per subtype)	Total Samples
Kangxi Tongbao Coins	Baoquan, Baoyuan, Man-Han East, Man-Han Ji	15	60
Pre-Qin Coins	Knife, Spade, Round, Ant-Nose	15	60

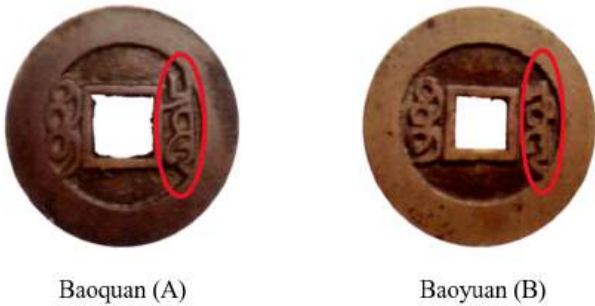


Figure 1: Subtle Character Stroke Differences (e.g., Baoquan vs. Baoyuan Kangxi Tongbao Coins)

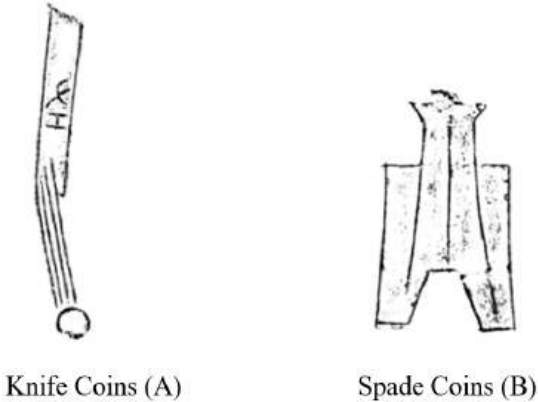


Figure 2: Pronounced Morphological Variations (e.g., Knife Coins vs. Spade Coins from the Pre-Qin Period)

3. Image Preprocessing

To ensure consistency during training, all coin images were resized to 96x96 pixels and converted to grayscale. These preprocessing steps standardized input conditions, optimizing the data for the CNN model while maintaining computational efficiency.

4. CNN Configuration

This study employed Google’s Teachable Machine, a user-friendly platform powered by TensorFlow, which utilizes the lightweight MobileNet architecture. MobileNet is optimized for efficient image recognition tasks and is particularly effective for use in hardware-constrained environments.

Table 2. Model Configuration Parameters for CNN

Parameter Name	Setting
Loss Function	Cross-Entropy
Learning Rate	0.001
Batch Size	16
Epochs	50 (short duration) and 500 (extended duration)
Image Resolution	96x96 pixels (grayscale)
Dataset Split	80% Training, 20% Testing

- **Loss Function:** Cross-entropy optimized the model by aligning predictions with actual classifications.
- **Learning Rate:** A rate of 0.001 ensured a balance between convergence speed and stability.

5. Training and Evaluation

Training was conducted in two phases—short-duration training (50 epochs) and extended-duration training (500 epochs)—to examine the effect of training duration on model performance. Classification accuracy was evaluated using both training and test datasets, with graphical analyses tracking accuracy trends across epochs. These visualizations helped identify potential overfitting scenarios and ensured the model’s reliability and generalizability.

Results

Outcomes for Kangxi Tongbao Coins

At 50 epochs, the CNN achieved a training accuracy of approximately 80%. However, test accuracy remained low, ranging between 30% and 40%. This discrepancy highlights issues with overfitting, as the model struggled to generalize beyond the training data.

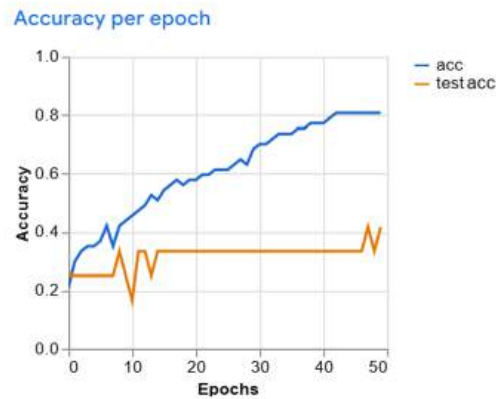


Figure 3: Blue line represents training accuracy, orange line represents test accuracy. The divergence increases as the number of epochs rises.

When training was extended to 500 epochs, the training accuracy further improved to nearly 100%. Despite this, test accuracy stagnated at approximately 25%–30%, with a more pronounced divergence between the training and test performance. These results suggest that extended training exacerbated overfitting rather than improving generalization.

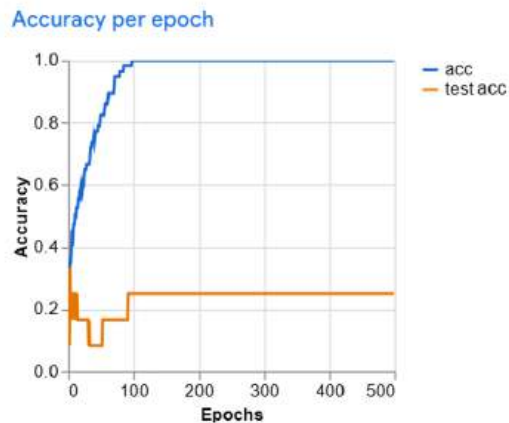


Figure 4: Blue line represents training accuracy, orange line represents test accuracy. The divergence becomes even more pronounced with a higher number of epochs.

Outcomes for Pre-Qin Coins

In contrast, classification performance for Pre-Qin coins was significantly stronger. At 50 epochs, the CNN achieved nearly 100% training accuracy, while test accuracy stabilized around 90%. This indicates a strong ability to generalize unseen test data, even during early training.

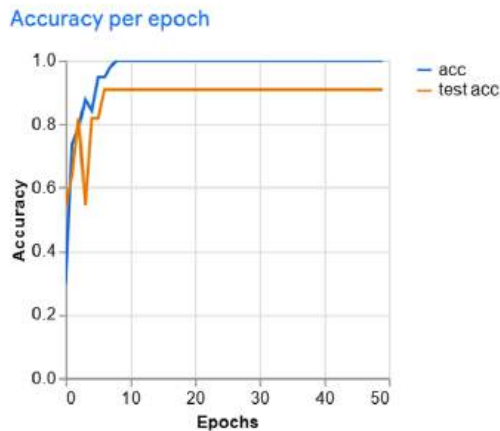


Figure 5: Blue line shows training accuracy, orange line shows test accuracy. After a few initial epochs, both lines rise quickly and stay close together, showing that the model performs similarly on both training and test data.

When training was extended to 500 epochs, both accuracies approached 100%, with the two lines converging and nearly overlapping. This result underscores the model’s consistency in classifying morphologically distinct coins and its ability to avoid overfitting on this dataset.

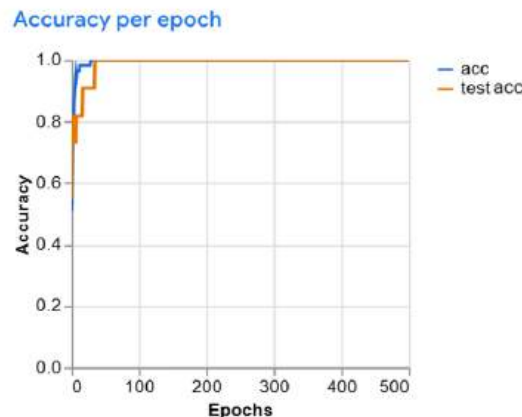


Figure 6: Blue line represents training accuracy, orange line represents test accuracy. The two lines converge quickly, almost overlapping in later epochs.

Discussion and Conclusion

The findings of this study provide valuable insights into the use of Convolutional Neural Networks (CNNs) for automating the classification of ancient Chinese coins, addressing a notable gap in numismatic research. By examining the stylistic diversity within Chinese coinage, this study explores the application of machine learning to coins with both subtle textual variations and pronounced morphological differences.

One key finding is the strong performance of the fine-tuned MobileNet model in classifying Pre-Qin coins, which display significant morphological diversity. Accuracy rates of 90%–100%, even with a limited dataset, demonstrate that CNNs can effectively handle coins with prominent

design features. This study represents the first successful application of machine learning to classify coins with pronounced morphological variations and suggests that small datasets can still produce reliable models for coins with substantial design differences.

Conversely, the lower performance of CNNs on Kangxi Tongbao coins, characterized by minor textual distinctions, highlights the challenges of distinguishing subtle variations with constrained data. Accuracy rates of 25%–40%, coupled with overfitting, point to the need for larger, more diverse datasets to improve classification and generalization (Goodfellow et al., 2016). Roman coin classification—which dealt with similar minor design variations—achieved an accuracy of 98% (Anwar et al., 2019), further illustrating the importance of dataset size for capturing fine details. Larger datasets are essential for improving models designed for coins with subtle design differences. These findings contribute to the development of machine learning tools capable of addressing both minor and major stylistic differences in classification tasks.

This study intentionally utilized small datasets, each comprising 60 images, to demonstrate that morphologically distinct coins can be classified effectively with limited data, while coins with subtle differences require larger datasets. Another contributing factor to this limitation is the scarcity of high-quality coin images, particularly for ancient Chinese coins. This issue is compounded by the lack of open-access, large-scale online databases. Addressing this challenge is important not only for future applications of machine learning in numismatics but also for advancing the field as a whole. Beyond expanding datasets, leveraging synthetic data generation techniques, such as Generative Adversarial Networks (GANs), may help supplement limited high-quality datasets. GANs have proven effective in reconstructing and enhancing damaged or degraded Roman coin images (Altaweel et al., 2023) and could similarly benefit the classification of ancient Chinese coins.

While this study evaluated the performance of the fine-tuned MobileNet model, future research could explore more complex architectures, such as ResNet or Vision Transformers (ViTs), to verify findings and expand applicability.

This study examines how stylistic diversity influences CNN performance and provides recommendations for developing comprehensive machine learning tools in numismatics. By addressing key research gaps and advancing the classification of coins with pronounced morphological variations, this study offers a foundation for further integrating machine learning into numismatic and archaeological studies.

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Bilingual Language Development and the Young Brain By Avalon “Avi” Barnard

Abstract

I started my discovery in Bilingual Language Development by analyzing data to form samples from Leaf Language Academy on reasons for enrollment. For this study, I surveyed 15 parents at Leaf Spanish Academy Preschool in Mira Mesa, California, about their perceptions of the benefits of a bilingual preschool and experiences with language development within their own children. From the responses I received from the survey, parents described that the best ways to support bilingual language development in their children included actively speaking Spanish at home, listening to Spanish TV and music, good relations with staff at Leaf Spanish Academy, and reading books in Spanish. All of these forms of immersion are backed by the research discussed earlier in this paper. The overall reasons for the choice of a bilingual preschool lie in the fact that 40% of respondents to the Leaf Spanish Academy survey stated that their enrollment of their child in a Spanish preschool was to “support communication with family members who speak the second language.” Through promoting learning a second language, we can create a more empathetic society that values the preservation of culture and the importance of communication. From the responses I gained on my survey, it’s clear to see that the main reasons for enrollment include the ability to communicate with family and the ease with which preschool-age children learn languages. Parents seem to believe in the benefits of a bilingual education and largely support their children in language learning in and out of preschool.

Introduction

43% of the world’s population is bilingual- are you? ¿43 por ciento del mundo es bilingüe, eres tú? Children exposed to more than one language early in life tend to learn to speak that language more fluently, more quickly, and with greater ease than their monolingual peers (Liwiński, 2019). Research shows that children exposed to more than one language early on often excel in math, form deeper connections with diverse people, and gain access to broader academic and career opportunities (Liwiński, 2019). "Kids are natural language learners. Children entering a second-language preschool often begin speaking their new language within just 1–2 weeks, and many reach conversational fluency in as little as three months” (Fibla et al., 2022). Children need as little as 10–25% exposure to a second language to begin acquiring it meaningfully (Fibla et al., 2022). Why not give them that opportunity?

This natural ability children have to acquire language lays the foundation for understanding what it means to be bilingual. To explore this concept more deeply, it’s important to clarify how “bilingualism” will be defined and discussed in the context of this paper. Within this paper, “Bilingual” will refer to an individual who is fluent (appropriate for their age and stage of development) in two languages. Fluency is defined as the ability to express oneself easily and articulately. Within this definition of bilingualism, several distinct categories emerge, such as compound, subordinate, and coordinate bilingualism. Compound bilingualism occurs when two languages are learned and acquired simultaneously within the same environment (or “context”),

often in infancy or youth. In such cases, the two languages are often used interchangeably and in overlapping settings. In contrast, subordinate bilingualism refers to individuals who learn a second language later in development (often in a structured setting, such as a school), and typically demonstrate stronger proficiency in their first language than their second. Coordinate bilingualism describes individuals who acquire two languages in separate contexts, resulting in distinct linguistic systems for each language (Fibla et al., 2022).

The following sections will provide an overview of early bilingual development, ways to support bilingual development, and the influence of public policy on bilingual education. This background is intended to frame the present study, a pilot investigation involving a small sample of parents whose preschool-aged children are enrolled in an immersive Spanish program. The study uses a qualitative approach, drawing on cross-sectional survey data collected as part of the research project to explore parents' perspectives. Specifically, the study explores parents' motivations for choosing an immersive bilingual environment, their observations of their children's language development, and their perceptions of the overall impact of early immersion at this developmental stage. The aim is to better understand how families experience and interpret early bilingual education, and to inform educators and policymakers about how to more effectively support parents and children in navigating and engaging with dual-language learning opportunities.

Background & Literature Review

Early Bilingual Development

Language is the basis of communication, understanding, and connection. The building blocks that create language are essential to a strong foundation. Understanding the way we develop language is integral to this project and bilingual language development. From the first moment of birth, infants are immersed in the world of sound - bombarded with particles of noise, and streams of phonemes that gradually begin to take on meaning. Even from these earliest hours of life, infants enter the Pre-Linguistic phase, characterized by the ability to produce non-speech sounds (i.e., cooing, crying, grunting, and squealing). While there are around 600 consonant sounds and 200 vowel sounds across all the world's languages, each individual language typically uses only about 40 of these sounds—called phonemes. Phonemes are the smallest units of sound that can change the meaning of a word (for example, how “bat” and “pat” differ by one phoneme, but have entirely different meanings as a result of one sound). Infants are born with the ability to discriminate phonemes from all the world's languages, but by around 10 to 12 months, this ability narrows as they become more attuned to the specific sounds of the language(s) they hear regularly. In other words, infants must quickly figure out which phonemes are relevant in the language(s) they are exposed to before they can begin to recognize and produce the words built from those sounds, reflecting their innate capacity for sound differentiation (Kuhl, 2004) (see Figure 1, the universal speech perception). This distinction between phonetic units is described as “categorical perception,” shown in the grouping of speech sounds into categories. That means

instead of perceiving sounds along a smooth continuum (e.g., slight variations of /b/ and /p/), they start to group sounds into categories that matter in their language.

This stage of expression and mimicry helps infants start to internalize the phonetic building blocks for the language they develop. For bilingual families, the formation of sounds within both languages allows the infant to create a “babble” using the phonetics of either language. At the six-month mark, infants reach the “Canonical babbling” stage, where they begin to produce the sounds of the language(s) they are exposed to. During the canonical babbling phase, infants begin to recognize patterns within the sounds they hear by tracking the frequency and patterns of sound. This recognition aids babies in predicting which sounds are most important for their language, allowing them to identify and learn the phonemes of their language. Around the 6th month mark, infants begin to focus on their native language and lose their ability to distinguish sounds not a part of their used language[s]. (California Department of Education, 2025) Babies become less able to perceive phonemes from languages they don’t hear often, which is why adults often struggle to distinguish sounds in languages they weren’t exposed to as infants, contributing to the loss of foreign language perception. Within this critical time, language-specific production occurs, leading to first words around 1 year. All infants' developmental milestones are different and occur on their own timelines, so variation is to be expected (Kuhl, 2004). In summary, babies use statistical learning to identify sound patterns, categorical perception to distinguish phonemes, and over time, they begin to lose the ability to perceive foreign language sounds, making their auditory system highly specialized for the languages they are exposed to. All of these processes are part of the brain’s natural adaptation to the language environment and are critical to development.

Benefits of Bilingualism

Although most agree that the learning of a second language is enriching to a child's life, a few widespread negative myths remain prevalent about bilingualism. Some believe that bilingualism can be detrimental to language development, leading to delays and disorders. This misconception sprang from early 20th-century research, which evaluated bilingual children’s language abilities in each language separately, rather than considering their combined linguistic knowledge. The approach overlooked the full scope of language development within bilingual children and underestimated the true capabilities and richness of a varied multilingual vocabulary. This myth does not occur within a vacuum - it’s the result of majority bias and prejudice against minority languages, as well as pseudo-research on early development. Additionally, early studies often did not control for socioeconomic status or the amount of resources available to the child-youth from immigrant or lower socio-economic backgrounds are more likely to face environmental stressors and limited educational results, aiding the guise of lowered development, skewing results. Xenophobic and assimilationist attitudes contribute to the spread of misinformation on this topic, often perpetuating harmful and negative stereotypes. A second myth is that learning a second language is too difficult for children. It might seem intuitive that children learn language quickly due to their age and cognitive flexibility, but this

hasn't always been the prevailing belief. The concern that acquiring a second language might interfere with learning the first language is a skill that must be taught rather than an innate human capacity. Contrary to that, there is an abundance of evidence that bilingual children develop language skills on a typical trajectory and can thrive in both languages. These myths are important to be aware of and continue to challenge, especially when working with prospective bilingual students and their families.

Positive Outcomes: Academic Success, Cognitive Skills, and Executive Functioning

Not only does bilingualism aid a person's ability to communicate, but it also has been shown to correlate with higher test scores, increased ability in mathematics, and better working memory. (Bialystok 2018) Students who were enrolled in bilingual language programs often outperformed their monolingual peers in mathematics and state exams (Bialystok, 2018). These differences in performance can be explained by the fact that bilingual children learn to differentiate between different languages and potential cognitive interference in order to speak the "correct" language in a context. This ability to filter out information and switch tasks more effectively aids in the understanding of complex concepts and representational abilities.

The effectiveness of differentiation and conceptual learning can be understood through the Dual Coding Theory, first proposed by Coding Theory, which suggests that the brain processes stimuli in two ways: verbal and non-verbal. The theory posits that associating a concept with a sensory stimulus increases the likelihood of successful retrieval. For bilingual youth, this theory proposes that information about language is stored both ways: in the verbal code (with distinct codes for each language), as well as the image-based code. For example, a child exposed to English and Spanish might encode "apple" and "manzana" as two separate verbal codes, but the ripe red image that occurs in response to both words will be the same for both. This dual usage of encoding can lead to increased retention and comprehension, as it "trains children to focus their attention on the relevant variables in the context, particularly information that is ambiguous or contradictory" (Bialystok, 2018). Curating the important parts of sentences and information increases reading comprehension as well as overall language development and understanding. In this case, a developmentally appropriate step would be forming sentences in a second language and understanding the meaning of given instructions.

Improvement in Socioemotional Development

Many children are put in programs of bilingual education for the purpose of fostering growth and connection with people in their lives who don't speak the majority language- for others, it's about keeping up with changing times and creating an environment in which their child will be successful. One such form of success is the improvement of social-emotional skills found in many bilingual children. Bilingual children have been shown to be more likely to understand the communication needs of others, recognise false beliefs and other languages (Singapore University of Technology and Design, 2023). A function strengthened by the learning of a second language is inhibitory control, which is the ability to stop and think before acting and

suppressing impulses, adding to self-control and regulation. Functions like this can lead to earlier childhood independence as well as accelerated development and confidence. These increased capabilities at an earlier age point towards some of what parents are hoping for by enrolling their child in a bilingual education program (Singapore University of Technology and Design, 2023). Another function of a bilingual education can be the increased cultural awareness and connection to heritage. Connecting with members of a family who are unable to speak the majority language allows for a larger sense of cross-cultural unity and intergenerational collaboration. Another study done by Huang et al. (2024) at the University of Bamberg, Germany, examines the correlation between second language learning and social-emotional development. The researchers found that the ability to communicate in more than one language made children not only more likely to express their feelings but to engage in prosocial behavior and have fewer behavioral issues (Huang et al., 2024). As well as most things in the process of child development, the input of caregivers and guardians is paramount; a strong child/parent bond (or child/teacher) has been linked to greater receptivity of the child to language learning and the introduction of a second language. The inverse of this also occurs, in which the learning of a language brings a child closer to a loved one due to the new form of shared communication.

Brain Findings

When considering the development of a child and its relation to language, a large emphasis should be put on the way that the young brain develops during this crucial period. Understanding the connection between language development and the brain starts in the cerebrum. The cerebrum is the largest part of the brain and contains the left and right hemispheres. It controls high-level functions such as movement, memory, and thought. Within the cerebrum are the cerebral cortex and the white matter. The cerebral cortex is also known as “grey” matter, which aids in information processing (such as language processing), while white matter helps different parts of the brain communicate. Bilinguals have been shown to have both more grey matter and white matter than monolingual people (Taylor et al., 2022). This increase in overall matter points to bilinguals' brains being potentially more efficient and possibly quicker at processing information. This can be attributed to the strengthening of neural pathways for multitasking and is referred to as the “Foreign Language Effect,” coined by David Robson (Robson, 2022). This effect explains how “Switching between languages can influence people’s financial decision-making and their appraisal of moral dilemmas” (Robson, 2022). These cognitive improvements and usage of rational decision-making provide for another demographic of those who benefit from a second language. The increase in grey matter and cortical volume is shown in the diagram below.

Aside from general brain matter density, people fluent in more than one language have been shown to experience lower rates of dementia and Alzheimer's. A study conducted at UCLA found that speaking a second language (in this case, Spanish or Farsi) delayed the onset of Alzheimer's as much as four years, building up a “cognitive reserve” against the disease (Mendez

et al., 2020). It's important to note that a second language doesn't stop the disease, but it does repress symptoms and lead to less impairment.

Sociocultural & Political Impacts

Within a professional career, the ability to speak more than one language opens doors for opportunities and connections. Within a Polish study, it was found that “language skills are positively correlated with wages,” with a 32% increase for Spanish and a 22% increase for French (Liwiński, 2019). Giving a child these advantages will aid them far beyond simple communication and allow for more opportunities later in life. This is echoed in my study, as nine out of the fifteen parents surveyed cited gaining “a competitive advantage in future academic or career opportunities” in aiding their decision to put their child in a bilingual preschool. In a newly competitive elementary and kindergarten field, it's become a top priority for parents and teachers alike, especially those who might wish to enroll their child in one of California's dual-language enrollment programs (of which 80% teach Spanish). Beyond the material benefits for a child exists the reality of living in the greater world, in which English is not the only language spoken and most likely will not always be the default. Along with cultural barriers that are dissolved by open communication in other languages, it allows children to grow into global citizens who can critically evaluate information for themselves and become value-based decision makers.

Importance of Language Preservation

The ignorance of minority languages and the argument for a monolithic culture, just because English happens to be widely used, ignores the possibilities of a more connected and empathetic world. Language erasure and the prioritization of a monolingual culture have been recurring themes within American language and culture studies. For instance, consider the case of Eyak, primarily spoken in central Alaska and a Na-Dené language, whose last native speaker passed in 2008. The language is now considered “dormant” due to the suppression of aboriginal languages and the extension of English within Alaska (The Native Village of Eyak, 2025). Oral histories and traditions are lost in this glacier of language communication after the systematic eradication of other languages. These patterns can even be seen today under the current administration, as bilingual and English as a second language programs have been federally decimated. Programs such as Obama's Bilingual Education Act are in peril of being repealed or cancelled (US Department of Education, n.d.; Villegas & Garcia, 2025). Patterns like this of loss can be avoided through education and funding for bilingual programs. Through fighting for the continuation of programs like these and raising awareness of the importance of learning a second language, we can keep our heritage alive and better understand others.

Methods

For this study, I surveyed 15 parents at Leaf Spanish Academy Preschool in Mira Mesa, California, about their perceptions of the benefits of a bilingual preschool and experiences with language development within their own children. The people I surveyed had children between the

ages of 2 and 5 and had been attending the preschool for lengths of a week to 3 years. Parents of girls and boys were surveyed, and a total of six languages and backgrounds were represented within the population (Spanish, English, Korean, Japanese, Armenian, and Russian). Leaf Spanish Academy specializes in full immersion as well as music and movement-based learning techniques, along with traditional artwork and learn through play methods. Paper surveys were administered on clipboards (to be completed by hand) during the drop-off session over two days, as well as sending out an online form with the same questions. The survey included ten questions (five multiple choice and five short answers), and took on average from 4 to 10 minutes for caregivers to complete. The questions were structured to allow parents to respond freely and not be prompted to a specific answer. Answers were not linked to parent or child names and will remain anonymous for the sake of their privacy.

Data Analysis Plan

The study made use of a qualitative analysis, in which the author read through participant responses to identify major themes, which were related to the study's aim and questions. This included understanding the percentage of children who would go on to continue learning a second language, as well as those who would not. Another factor that was found to be important to analyze was the challenges in learning a second language and how they were aided, as this information will also aid in creating a guide for parents and teachers interested in preschooler language development.

Results

All responses were reviewed by the lead author. Emergent themes were identified through a qualitative analysis process, and responses were organized according to these categories. Results are presented below according to theme.

Theme 1: Supporting Bilingual Development

From the responses I received from the survey, parents described that the best ways to support bilingual language development in their children included actively speaking Spanish at home, listening to Spanish TV and music, good relations with staff at Leaf Spanish Academy, and reading books in Spanish. All of these forms of immersion are backed by the research discussed earlier in this paper, and it seems that the parents who reported successful immersion (qualified by the usage of Spanish in and out of the preschool setting) had employed these techniques.

All parents described their child's adjustment to the preschool differently, with some parents having moderate difficulty with the separation, while others said the transition was seamless. According to my survey, the factors that influenced the transition were primarily previous exposure to Spanish, overall confidence, and relations with teachers. Many have utilized their partners' experience in Spanish (three parents reported having partners who spoke Spanish or took the language in university), which, as demonstrated, improves both child-parent relations

and understanding and fluency. The most effective forms of language development rest in large quantities of time spent with invested and fluent instructors.

Theme 2: Reasons for Enrollment

The overall reasons for the choice of a bilingual preschool laid in that 40% of respondents to the Leaf Spanish Academy survey stated that their enrollment of their child in a spanish preschool was to “support communication with family members who speak the second language,” as well as one parent citing “communication with [his] grandparents” as a primary reason for enrollment. The second most prevalent reason was due to the mental plasticity of preschoolers and how their brains were “like sponges and would learn a second language quicker now than in the future. Interestingly, one of the fifteen surveyed parents stated that they did not expect their child to have access to any more bilingual education after their time at Leaf Spanish Academy. This response was unusual for the survey as it was the only response of this nature and brought up many questions as to his child's enrollment within the preschool.

Limitations

Some limitations within my experiment were the usage of a survey, as it related to the parents' accurate depiction of their own and their child's behavior, which might have been swayed within the parameters of this experiment through the context of the survey and those asked. Another issue was the number of respondents, as I was only able to gather fifteen complete responses, whereas a study of a larger scope could have provided a better representation of the opinions of parents on the topic of language development and bilingual education. Ideally, I could have gathered around 20-30 responses from all parents of children attending the preschool, but obviously, this was not successful. Therein, a larger sample size could have provided more solid evidence on this front.

Future Directions

For the future of this research and paper, I would like to continue my inquiry into bilingual language development through the lens of possibly an expanded paper with a larger data pool or a series of infographics explaining the reasons parents might enroll their child in an immersion preschool. For the expanded data pool, I might return to the preschool during the next school year and survey incoming parents, as well as possibly expanding my study to other bilingual preschools within my area, seeing how the demographics of those schools might change or alter my responses. These infographics will serve to inform parents and teachers who might be interested in supporting or sending their children to these programs, as well as promoting knowledge about bilingual development within children and dispelling common myths. This will aid understanding and acceptance of bilingual families and their children within my community, as well as in the larger sphere of education.

Conclusion

Through the advantages in career, connection, and culture, aiding a child in learning a second language is paramount for the development of a well-rounded global citizen. From the responses I gained on my survey, it's clear to see that the main reasons for enrollment include the ability to communicate with family and the ease with which preschool-age children learn languages. Parents seem to believe in the benefits of a bilingual education and largely support their children in language learning in and out of preschool. These factors heavily influence the enrollment of young children in bilingual or second language preschools, creating a network of children ready for a global future. The importance of funding and support for these programs can't be understated, and it's our duty as citizens of our nation to ensure that they continue to run and educate. Through promoting learning a second language, we can create a more empathetic society that values the preservation of culture and the importance of communication.

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The Impact of Social Media On Adolescents By Raj Gandhi

Abstract

Social media use among adolescents has increased dramatically over the past decade, raising concerns about its effects on mental health, social development, and overall well-being. This paper examines the positive and negative impacts of social media on teenagers, focusing on trends in platform popularity, patterns of use, and associated psychological outcomes. Research shows that platforms like Instagram, Snapchat, and TikTok dominate adolescent use, which offers opportunities for social connectedness, self-expression, and peer support. However, excessive or emotionally driven use has been linked to negative outcomes, including depression, anxiety, sleep disturbances, body image issues, and cyberbullying. Studies reviewed in this paper include empirical research, longitudinal surveys, and self-report questionnaires. These are primarily conducted with U.S. adolescents. Overall, this sample of literature points to a complex relationship: social media can promote social engagement and emotional support but also contribute to psychological distress, particularly when use encourages social comparison, disrupted sleep, or exposure to harmful content. Limitations of the research to date include its reliance on self-reported data, cross-sectional designs, and limited generalizability across diverse populations. The findings highlight the need for targeted interventions, evidence-based parental guidance, and more longitudinal and experimental research to inform the development of strategies that promote healthy social media use and protect adolescent mental health.

Popular Social Media Websites For Teens

Social media usage among adolescents and young adults (i.e., individuals aged 10-32) has seen massive shifts in the recent decade, with different platforms gaining or losing popularity over time. For instance, in 2018, Facebook, which was once the dominant social media platform, shows its teen user base sharply declining, as only around half of adolescents report using it (Anderson and Jiang 2). According to more recent data from 2024, the trend has intensified because adolescents are now shifting to more engaging platforms that have quick interactions (Faverio and Sidoti 4). As of recent surveys, platforms like YouTube, Instagram, and Snapchat are now the most frequently used among adolescents. This shift aligns with what has occurred over the past decade, with adolescents favoring real-time communication and short-form over medium length written content (Anderson et al. 1). Additionally, adolescents now spend an increasing amount of time online, with nearly half reporting near-constant internet access, a rise from 2014-2015 when only a quarter of adolescents claimed to be online so frequently (Vogels et al. 8). This change in usage patterns highlights the growing engagement with platforms that facilitate quicker, more social interactions, showing a bigger shift in teen social behavior.

Social media continues to control American adolescents' lives more and more, influencing the way they talk, express themselves, and look at the world. A Pew Research Center survey conducted in 2014-2015 indicated that 24% of teenagers say they are online "almost constantly," showing how involved these platforms have become in daily life (Vogels et al. 8). The same

survey repeated in 2022 Pew Research Center survey indicated that 95% of adolescents watch YouTube, 67% use TikTok, and a variety also use Instagram (62%) and Snapchat (59%) (Vogels et al. 10). As of 2023, adolescents used social media for an average of almost 5 hours per day (Statista Research Department 1).

Impact of Social Media on Teen Mental Health

The usage has given medical professionals a warning. For instance, the American Psychological Association warned that excessive social media usage can potentially cause depression, anxiety, and low self-esteem in teenagers, especially if teenagers use social media to seek validation or engage in unhealthy comparison (Hamilton, Dreier, et al. 16). Moreover, other researchers highlighted the issue of how the platform design is configured to invite addictive behaviors and emotional dependence (Vaid and Harari 10). Its negative effects, like its association with increased depression and anxiety levels, are a serious concern to most experts (Khalaf et al. 4). Studies have shown that excessive social media use has been connected to worse sleep quality, lower satisfaction with life, and less exercise, particularly in girls (Buda et al. 2). There may be a link because excessive social media use can disrupt sleep and reduce exercise and can harm health. Also, it encourages unhealthy comparisons that lower self-esteem and life satisfaction shown mostly in girls who may be more emotionally affected.

On the other hand, social media can benefit adolescents by enabling ways of expression and community integration, particularly in some moderation and with guidance (Correa et al. 1). For instance, brief, and more purposeful exposure to social media has been associated with enhanced mood and psychological functioning. Also, this is particularly if use is limited to under three hours per day (Hilty et al. 5). Moreover, other studies show that the influence of social media on mental health can vary across gender as research indicates that girls spend more time on social media compared to boys. The survey findings revealed that boys are more likely to spend time gaming, and girls are more active on social media (Leonhardt and Overå 5). The effects are dependent on the social media platform utilized, and more research is needed to understand these differences (Schønning et al. 1). Studying the impact of social media on adolescents is essential because it allows us to shape a healthier and more informed future for the next generation. This will make it so they can handle the digital world in a way that supports their well-being.

Purpose Of Review

The purpose of this review is to examine the impact of social media on adolescents, a topic that has become increasingly relevant because these platforms play a big role in the lives of today's youth. Social media has the power to shape multiple aspects of adolescent development, including social interactions, self-esteem, and mental health (Khalaf et al. 2). Also, with the growing presence of platforms like Instagram, TikTok, and Snapchat, it is important to understand both the positive and negative effects these digital spaces can have. By reviewing existing research and exploring the different ways social media influences young people, this paper aims to provide an extensive understanding of the topic.

Depression and Anxiety

The correlation between depression and social media usage among American young adults has been an area of great concern with various studies examining the possible effects on mental health. Various methodologies such as surveys and self-report questionnaires have been employed to explain this phenomenon. For example, researchers asked 1,768 young adults (aged 19–32) about their social media use and depressive symptoms via standardized measures, including the Patient-Reported Outcomes Measurement Information System (PROMIS; Primack, Shensa, Escobar-Viera, et al. 1). Primack and his colleagues found that using social media platforms is tied to higher levels of depression and anxiety. In another study similar to this, researchers (2018) found that social media fatigue (i.e., tiredness with increased use of social media) predicted depression in teens, suggesting that those with greater screen time and fatigue experienced more depression (Dhir et al. 1). Within a separate longitudinal study, Norwegian adolescents filled in two rounds of surveys six months apart, allowing researchers to track changes over time in both social media usage and depressive symptoms (Brunborg and Burdzovic Andreas 1). The results showed that spending more time on social media linked to more signs of depression over six months, showing that using social media might be connected to mental health getting worse in teenagers over time.

These and other studies concluded that there was a relationship between social media use and increased symptoms of depression. For instance, teenagers who spent more time on platforms like Instagram experienced more negative feelings and depression, a trend that increased when the subjects followed more strangers on these platforms (Trub et al. 1). This can connect with findings from another study that found social media use can lead to negative social comparisons, which contribute to depressive feelings (Steinsbekk et al. 2). The social media-depression relationship is complex, and it has been shown in some research that it is not so much the amount of usage, but the form of social comparison and peer contact that is most significant in generating these negative results (Primack, Shensa, Escobar-Viera, et al. 2). The reasons social media affects depression includes seeing others posts and feeling worse about themselves, feeling anxious about missing out on events, getting tired from too much screen time, and facing negative online interactions like bullying. In addition, social media use can disrupt sleep, reduce time spent with friends in person, and increase loneliness. All these factors help explain why teens who use social media more may experience more depression over time.

Although findings of such studies provide good insight, there are considerable limitations. People may not be accurately or thoroughly reporting their use of social media or depression symptomatology (Liu et al. 13). Also, despite findings of relationships between the use of social media and depression in some research, the effect sizes were fairly small (Brunborg and Burdzovic Andreas 2). These small effect sizes suggest that various factors, including peer interaction or life stressors, may help increase depressive symptoms rather than just social media use alone.

Several of these studies failed to fully account for confounding variables, like socializing offline (Brunborg and Burdzovic Andreas 3). Finally, the research was primarily on young adults

from specific geographic regions, such as the United States (USA), and might not be as generalizable to a broader global population (Primack, Shensa, Sidani, et al. 1). Researchers must conduct further studies to examine these complex interconnections and develop better methods to overcome the current limitations. These studies show the importance of understanding these connections to develop better prevention and/or intervention strategies for improving adolescent well-being in the digital age.

The growing use of social media among adolescents has raised concerns about its potential link to anxiety as well. Research involving 467 Scottish adolescents between 11-17 years old concluded that higher usage of social media, particularly in the evening, was associated with lower quality sleep, lower self-esteem, and higher anxiety levels (Woods and Scott 1). Similarly, a study on U.S. young adults aged 18-22 identified that emotionally interacting with social media, such as to seek attention or comparison, led to high anxiety levels (Vannucci et al. 1). The methods used in both studies were survey and self-reported measures, and allowed researchers to quantify social media usage and emotional states like anxiety. These studies show that late night or emotionally driven social media use increases adolescent anxiety

Nevertheless, studies on anxiety have some drawbacks. For example, the Scottish study relied on self-reported information (same as U.S studies), which can be biased because participants may not report social media use and anxiety symptoms accurately (Woods and Scott 3). Similarly, while the U.S. study focused on emotional involvement, it did not examine the specific social media sites or the long-term impact of the behaviors on anxiety (Vannucci et al. 1). Along with that, the two studies utilized cross-sectional designs, like studying a group of people at one moment in time. Researchers collect all the information at once, and help find patterns quickly but don't show changes over time. Therefore, they cannot establish a causal relationship between social media usage and anxiety (Arikan et al. 1). To conclude, a Chinese adolescents' study determined that social anxiety was related to internet addiction through both loneliness and coping styles (Dong et al. 1). A U.S. study found problematic social media use was associated with increased depression, anxiety, and social isolation, but because the sample only included 403 undergraduates from one university, the findings may not apply to everyone (Meshi and Ellithorpe 2). Collectively, these studies suggest a correlation between anxiety and social media, but further research is needed to achieve a complete understanding of cause and the effect.

Sleep Disruptions

Sleep disruption, also known as interrupted sleep, refers to the experience of frequent awakenings or difficulties falling back to sleep during the night (Vernon et al. 1). Experts recommend that adolescents get 8 to 10 hours of sleep per night for healthy development and functioning (Hirshkowitz 1). However, social media habits often cut into this needed sleep time. Increased social media use in teenagers has been linked with sleep disturbance, which in turn negatively impacts their academic performance and overall well-being. Specific habits like nighttime message checking, notifications, and being awake late at night through social media use are significant predictors of disturbed sleep (Levenson et al. 1). For example, the blue light emitted from screens suppresses melatonin production, the hormone responsible for regulating the

sleep-wake cycle. This makes it harder to fall asleep and negatively affects circadian rhythms (Tandon et al. 4). The Fear of Missing Out (FoMO) phenomenon drives adolescents to frequently check social media during the night too. A study among American teenagers found that social media use at night resulted in reduced sleep quantity and quality, and affected their academic performance and stress levels (Tandon et al. 4). Furthermore, teenagers who used social media reported higher levels of school burnout, showing the interconnection between sleep disturbance, academic performance, and psychological well-being (Evers et al. 2).

These results indicate that the ongoing use of social media can interfere with the sleeping pattern, which consequently impacts the academic performance and psychological well-being of teenagers. The participants of the studies were mostly U.S. adolescents, and even Taiwanese adolescents suffering, and fixing sleep problems could help them do better in school (Tandon et al. 1; Evers et al. 1). Procedures typically included surveys and questionnaires to assess sleep quality, social media use, and academic performance. An example can be a survey that quantified social media usage, school burnout, and sleep discovered that adolescents with more sleep disturbance showed more burnout and worse school performance (Evers et al. 1; Hale et al. 1).

The drawbacks of these studies are that they are self-report based, which can have some errors, and most of the studies focused on specific geographical locations like Taiwan or America, so the generalizability of the study was low (Levenson et al. 1; Hamilton, Stig Jørgensen, et al. 1). Additional research using longitudinal and experimental designs is therefore needed to explain these relationships. This matters because adolescents' heavy use of social media could harm not only their sleep but other factors, like their education, mental health, and long-term success if this misuse continues over a long period of time.

Cyberbullying

Bullying someone through social media, known as cyberbullying, is increasingly prevalent in today's youth (Samantha B 1). Cyberbullying is now a common occurrence related to the large-scale use of social media by teenagers, which has significantly influenced their mental well-being and health. A significant body of research, including studies conducted on U.S. high school students, explores the relationship between frequent social media use and experiences with bullying. For instance, the 2023 Youth Risk Behavior Survey (YRBS) gathered data from a large, nationally representative sample of high school students. This study utilized self-reported surveys to assess how often adolescents used social media and how this use correlated with their experiences of bullying, online and in person. Researchers asked participants about their social media habits, feelings of sadness, and suicidal thoughts to understand connections between these experiences and their mental health outcomes (Young et al. 1). Youngs' study showed many students use social media daily, and using it a lot is linked to feeling sad and being bullied. They found girls and LGBTQ+ students are affected at higher rates than their male classmates and non-LGBTQ+ peers.

Similar studies have consistently shown that adolescents who spend more time on social media report higher rates of being bullied, usually in digital spaces, with those at higher risk being more likely to experience psychological distress (Samantha B 1; Young et al. 3). The findings

point to the crucial need for better awareness and preventive measures to deal with cyberbullying and its effects. These results highlight the vulnerability of youth in a digital age where bullying can extend beyond school grounds and be relentless. Although, they do not capture the full complexity of how different types of social media platforms impact the prevalence or intensity of cyberbullying (Fahy et al. 1; Dredge et al. 1). Despite these challenges, these findings have a big impact for policymakers, educators, and parents who want to decrease the harmful effects of social media on adolescents and develop interventions that promote safer online environments (Chan et al. 4; Craig 2).

Body Image Issues

Many adolescents in the U.S. appear to be experiencing body image concerns, which may be influenced by their use of social media. This matters because body dissatisfaction can harm mental health and lead to unhealthy behaviors, like depression, extreme dieting, and disordered eating. The studies looked at U.S. adolescent girls and found that constant exposure to idealized body images online, especially on platforms like Instagram and Snapchat, often led to comparisons with others. For example, surveys and focus groups with girls aged 12–14 found that while the girls were confident and media-smart, they still compared their appearances to peers online (Burnette et al. 1). Similarly, research examining adolescents' online habits showed that using apps to share or view photos increased the chances of body dissatisfaction, because many judged themselves based on what they saw (Marengo et al. 2). In addition, studies involving surveys and interviews with high school girls showed that being teased about appearance and seeing peer images online was connected to more negative thoughts about their own bodies (Jarman et al. 1). Research focusing on parental influence found that adolescents who heard more appearance related comments at home would feel worse about their bodies, especially when combined with social media use (Burnette et al. 1).

These findings suggest that even when adolescents recognize that images are unrealistic, social media can still negatively affect how they feel about themselves. While the methods in these studies varied, most used surveys and interviews to understand adolescents' thoughts and behaviors. Each study had its limits, for example, many focused on small or specific groups, mostly girls, and lacked long-term follow up to assess later effects. Overall, social media appears to be linked with how adolescents, especially girls (as boys don't focus too much on it, instead, video games), view and feel about their bodies.

Social connectedness

Social media supports adolescent relationships in different ways, including building social connectedness and facilitating emotional communication. Social connectedness is a positive outcome of social media use among adolescents, promoting more communication and strengthening relationships (Winstone et al 2.; Angelini et al. 2). Social media platforms enable teens to maintain and expand their social networks beyond geographical limitations, allowing for more frequent and diverse interactions with friends and peers (Al-Jbouri et al. 1). This connectivity helps teens feel supported and understood, contributing to enhanced friendship

quality and a sense of belonging (Angelini et al. 2). For instance, active engagement on social media like sharing experiences and participating in group discussions, has been shown to improve perceived friendship quality and reinforce positive group norms (Angelini et al. 3). Moreover, social media offers adolescents' opportunities to stay connected with online and offline friendship networks. This can bridge social gaps and increase their overall sense of social integration (Al-Jbouri et al. 3).

However, social media can possibly reduce real-life interactions, which may harm teens' social skills and increase feelings of loneliness. Social media enables communication that supports emotional bonding and peer support, and can help during adolescent development (Fredrick et al. 4; Phua et al. 2). By giving spaces for self-expression and feedback, teens can receive encouragement from their social circles and boost self-esteem and mental well-being (Fredrick et al. 4). Social platforms also allow for fast and convenient exchanges, making it easier for teens to maintain relationships despite busy schedules or physical distance (Winstone et al. 4). This communication not only helps social connections but can also displace feelings of isolation, making a more inclusive social environment (Winstone et al. 4.; Fredrick et al. 4). Additionally, the various features of social media, such as messaging, commenting, and sharing multimedia, empower adolescents to engage with their peers actively, reinforcing social bonds (Phua et al. 2; Winstone et al. 4.)

Conclusion

The research on social media and mental health in young people suggests social media can have both good and bad effects on adolescents. Some studies say social media helps teens stay connected with friends and express themselves. However, numerous studies also show that social media use is linked to problems like feeling sad or anxious, being bullied online, trouble sleeping, and feeling bad about how they look. The effects are different for each person and depend on how much and how they use social media. One strength in this research is that a large portion of studies follow teens for a long time (Steinsbekk et al. 4). This helps researchers see how social media affects mental health over months or years, not just at one moment. Multiple studies include a lot of participants, which means their results can apply to more teens from different places and backgrounds too. Having a diverse participant pool can enhance the reliability and generalizability of the results. On the contrary, many studies rely on teens telling researchers about their feelings (i.e., self-reported), which might not always be accurate and teens might say they feel worse or better than they really do. Also, many studies don't include enough teens from different races or cultures, so the findings might not be applicable for everyone. Some research also doesn't explain well why or how social media affects mental health. Lastly, some studies might have conflicts of interest, meaning researchers might have personal or financial reasons that could influence the results (Buda et al. 1).

Future studies should use different ways to learn more about social media's effects. For example, mixing surveys with interviews would give better information, utilizing a mixed methods approach. In addition, it would be helpful to do experiments where teens are randomly told to use social media for a limited time, like 2 hours a day, or to use it however much they

want. This should focus on adolescents between ages 10 and 21 because that is an important time for mental health. A study could be conducted focusing on specific age groups, such as junior high and high school students, to examine how differing social contexts impact their experiences. Such research would offer valuable insights into whether social media actively contributes to certain issues, or merely coincides with them.

Based on the existing literature, social media seems to be more harmful than helpful for young people's mental health. There is strong evidence showing social media use is linked to depression, anxiety, and being bullied online (Fahy et al. 1). While some argue that social media fosters a sense of connection among teens, the prevailing evidence suggests that its potential benefits are often outweighed by its detrimental effects. Many adolescents are more likely to experience declines in self-esteem and overall well-being as a result of their social media use.

To help protect teens' mental health, everyone needs to have a part. Teens should try to limit how much time they spend on social media and not compare their lives to what they see online because people usually show only the good parts. Parents can help by making rules, such as taking away phones sometimes, using parental controls to block harmful content, and watching for signs of depression or any negative symptom. If a teen is struggling, then parents should talk to school counselors or mental health professionals. Teens might have to show they are responsible, like doing well in school or chores before getting social media "privileges". On a larger scale, society should raise awareness about these problems through news. There could also be rules that stop people who bully others online from using social media. These steps can help teens develop healthier habits and reduce risks like anxiety or depression.

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An Electromagnetic Triggered Auto-timing Device for Measuring Gravitational Acceleration By Bing Zhou and Tu Hong

Abstract

Accurate measurement of gravitational acceleration (g) is essential in both physics education and applied science. Traditional methods, such as the pendulum method and free-fall method, require manual intervention to stop the timing. These approaches are limited by human error and complex operations. We hypothesized that an electromagnetically triggered auto-timing device, built with simple laboratory materials, would reduce random error and increase repeatability compared to manual methods. To test this, we constructed a circuit using a single-pole double-throw self-resetting switch (S_1) and a downward spring-loaded switch (S_2), enabling multiple stable measurements with a success rate of 98%. Our results showed that at a drop height of 1.893 m, the measured g was 10.043 m/s^2 with a percentage error of 2.354%. Compared with manual stopwatch measurements, the device demonstrated significantly lower volatility and error. These findings support our hypothesis that integrating electronic triggers into free-fall experiments can provide students with a simple, low-cost, and more reliable tool for measuring gravitational acceleration.

Keywords Gravitational acceleration, Electromagnetic triggering, Automatic timing, Experimental apparatus.

1. Introduction

The study and measure of g hold significant importance in science, engineering, technology and in daily learning, such as in verifying physical laws and designing large-scale structures. In a classroom setting, the measurement of g helps students grasp the fundamental principles of motion and force. Over the years, various experimental techniques for measuring g have been developed, including the classical free-fall method (1), the photoelectric gate timing method which reduces errors in manual timing, simple pendulum method (2), the use of modern smartphone sensors in line with technological innovation (3-5) and other methods (6, 7). After reviewing the aforementioned experiments, it was found that these methods involve relatively complex operational procedures. Manual timing methods, particularly those using stopwatches, are especially susceptible to errors caused by reaction time-such errors can lead to deviations of up to 0.2 seconds, thereby introducing a considerable percentage error in the measurement of g . In addition, some digital methods require expensive or specialized equipment, which limits their feasibility in daily classrooms. Therefore, there is a need for a device that is both low-cost and simple to build, while still minimizing human error. We designed a new device for measuring g using common laboratory materials. We hypothesized that an auto-timing device based on an electromagnetic trigger and electronic stopwatch integration would yield more stable and accurate measurements of g than manual timing. This experimental apparatus combines physical principles with electronic engineering, eliminating errors caused by human reaction time. Results

demonstrate that the device is both reliable and reproducible, offering a practical and affordable solution for physics education.

2. Materials and methods

2.1 Installation device

In the device designed in this article, the timing function of an electronic stopwatch is utilized. Its trigger control switch is modified and connected to the circuit. The circuit controls its starts and stops, enabling the recording of the time t required for a small ball to fall a certain height h with a single manual control, thereby obtaining g . Figure 1 shows the circuit diagram of the device, which includes a constant current power supply, a self-made electromagnet, a modified electronic stopwatch, and two switches S_1 and S_2 . S_1 is a single-pole double-throw switch, and S_2 is a single-pole single-throw switch. By controlling the two switches to start three circuits Loop 1 (L_1), Loop 2 (L_2), and Loop 3 (L_3) in sequence.

L_1 is composed of a constant current power supply, a homemade electromagnet and switch S_1 ; L_2 is made up of an adapted electronic stopwatch and switch S_1 ; L_3 is constructed with an electronic stopwatch and switch S_2 . In the initial state, switch S_1 is at terminal A, L_1 is conducting, and the constant current source supplies power to the electromagnet. When switch S_1 is rapidly toggled, it moves to terminal B, L_1 is disconnected, and L_2 is conducting. At this point, the small ball falls, and the electronic stopwatch starts timing. Then, switch S_1 returns to terminal A, and L_2 is disconnected. When the small ball falls to a certain height and hits switch S_2 , L_3 is conducting, the timer stops timing, and S_2 automatically resets to the disconnected state. At this point, the timer displays the time it took for the small ball to fall.

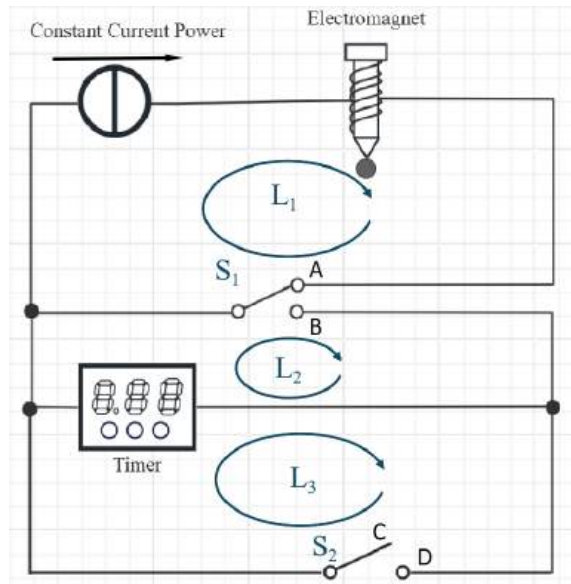


Figure 1. Circuit diagram

The device was fabricated according to Figure 1, as shown in Figure 2. A constant current power supply was used to power the circuit to ensure that a sufficient and stable current flowed through the electromagnet device. A heavy iron stand was used as the base, and a 1-meter-long hollow PVC transparent tube was inserted to serve as the height adjustment frame for the device. A 240-turn copper coil was tightly wound around a 13 cm iron nail to create the required electromagnet. A metal ball with a diameter of 1.9 cm and a mass of 27 g was attracted by the electromagnet at the bottom. A laser pointer was fixed near the iron nail to facilitate measuring the height h of the ball each time it dropped. To achieve the success rate and repeatability of this device, issues related to the fabrication of switches S_1 and S_2 need to be overcome.

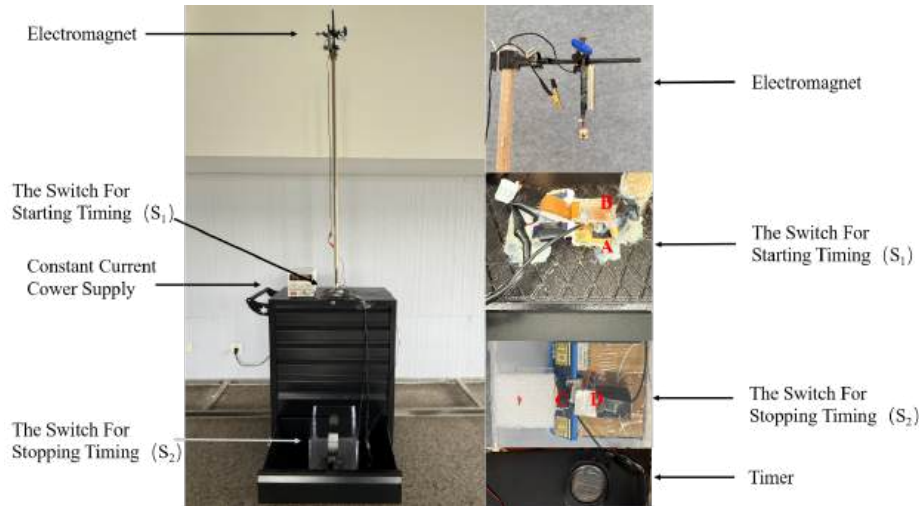


Figure 4. Experimental apparatus diagram

Switch S_1 : After the timer starts counting (when circuit L_2 is switched on), S_1 must be released immediately. If it remains engaged, the electronic stopwatch will repeatedly start and stop. The switch is a custom-built spring-loaded double-throw self-resetting switch. A rebound plate serves as the common terminal, with conductive copper foil attached to both its upper and lower surfaces. The base plate functions as terminal A of the double-throw switch, also covered with conductive copper foil, and connected to one end of the electromagnet. In its natural state, circuit L_1 is closed, allowing the ball to be held by the electromagnet. Above the rebound plate, a plate with copper foil attached is fixed as terminal B. The distance between the common terminal and plate B is minimized to reduce the error between the ball's release and the start of timing. Switch S_1 thus provides double-throw functionality, and thanks to its spring-return mechanism, it resets automatically without affecting the timing.

Switch S_2 : To stop the timer, switch S_2 is triggered by the ball's own weight. Once S_2 closes and circuit L_3 is switched on, it must be released immediately. This switch is custom-built as a spring-loaded push-down switch. To improve the experiment's success rate and repeatability, S_2 has both front and rear ends. In its natural state, the rear end is raised, forming rebound plate C,

and the circuit remains open. When the ball falls onto the marked red triangular area of the rebound plate, the front-end lifts and contacts the upper plate D in the circuit. At this moment, L_3 switches on, stopping the timer. During this process, the ball touches the rebound plate only briefly, so the conduction time of L_3 is very short, allowing only a weak current to pass through. To prevent timing failure, the design of S_2 has been continuously refined. After many trials, it was found that common microswitches and copper push-button switches on the market allow insufficient current conduction and lack sensitivity, leading to a low success rate. According to formula (1):

$$I = neAv \quad (1)$$

Where I is the current, n is the number of electrons per unit volume, e is the electron charge, A is the cross-sectional area of the conductor, and v is the drift velocity. We changed the contact surface to a curved shape to increase the contact area. Additionally, according to the formula:

$$v = \frac{\sigma E}{ne} \quad (2)$$

$$\sigma = \frac{1}{\rho} \quad (3)$$

Where E is the electric field strength, σ is the electrical conductivity, and ρ is the electrical resistivity. At 20°C, the ρ of silver sheets is $1.59 \times 10^{-8} \Omega\text{m}$, while that of copper sheets is $1.75 \times 10^{-8} \Omega\text{m}$ (8). Therefore, under the same E , $V_{\text{Silver}} > V_{\text{copper}}$. From this, it follows that a greater current passes through the silver sheet with lower ρ , so we replaced the original copper sheet with silver. Based on the lever principle, the rear end of the rebound board was extended to make the moment arm of the force larger than the resistance arm. At the same time, the rear edge angle was adjusted to about 20° to reduce force decomposition. After adjusting to a silver sheet switch, increasing contact area, and improving conduction time, the measures' success rate increased from 40% to 98%.

2.2 Operational Procedures

Align the electromagnet with the switch S_2 . Using a meter stick, measure the falling height of the ball, defined as the vertical distance from the tip of the electromagnet to rebound plate C on the switch S_2 . Repeat the measurement and calculate the average of the falling heights.

Adsorb the ball onto the electromagnet, then press the switch S_1 to release the ball. Record the time displayed on the timer. Repeat the measurement multiple times at the same height, calculate the average of the falling times, and determine g using formula (1). Vary different heights and measure g respectively. Before each measurement, inspect the device and reset the timer to zero.

3. Results and discussion

In high school physics learning, when an object with an initial velocity of 0 ms^{-1} , falls from a height of h , it undergoes free fall motion (ignoring air resistance), and g can be obtained using formula (4).

$$g = \frac{2h}{t^2} \quad (4)$$

We measured the falling height of the small metal sphere using a meter stick. This sphere was absorbed on the electromagnet, and released by pressing S_1 . The time taken for the small metal sphere to fall was recorded from the timer, and the value of g was calculated using the formula (4).

3.1 Compare the g at different heights

To evaluate our hypothesis, we measured g at four drop heights (1.893 m, 1.606 m, 1.401 m, and 1.206 m). According to formula (4), the value of g was obtained (10.043 ms^{-2} , 10.894 ms^{-2} , 11.482 ms^{-2} and 13.417 ms^{-2} , respectively, four-heights g -tests, Table 1. To reduce experimental errors, the ball was dropped seven times at each height, and the timer response time t was recorded. The relative percentage error of g was then calculated using formula (5), where the theoretical value of g should be calculated using the theoretical value 9.8 ms^{-2} .

$$\delta = \frac{|Measured\ Value - Theoretical\ Value|}{Theoretical\ Value} \times 100\% \quad (5)$$

We found that within the height range allowed by operating in the laboratory, since the sphere is a solid metal sphere, the effect of air resistance is minimal. Considering only instrument and random errors, at the height of 1.893 m, the measured g is 10.043 ms^{-2} with an error of only 2.354%.

Table 1. Timing test data for g measure device.

h (m)	1.893	1.606	1.401	1.206
t_1 (s)	0.62	0.54	0.50	0.43
t_2 (s)	0.62	0.55	0.50	0.43
t_3 (s)	0.60	0.54	0.48	0.43
t_4 (s)	0.62	0.56	0.50	0.42
t_5 (s)	0.62	0.54	0.50	0.42
t_6 (s)	0.60	0.54	0.50	0.42
t_7 (s)	0.62	0.54	0.48	0.42
t_{mean} (s)	0.614	0.544	0.494	0.424

$g \text{ (ms}^{-2}\text{)}$	10.043	10.894	11.482	13.417
$\delta \text{ (%)}$	2.354	11.017	17.020	36.741

Therefore, 1.893 m is the optimal height for measuring g in the laboratory. As the height decreases, the falling time of the sphere becomes noticeably short, resulting in larger δ (δ of g at 1.893 m, 1.606 m, 1.401 m, and 1.206 m: 2.354%, 11.017%, 17.020%, and 36.741% respectively, Figure 3 and higher measured values of g . At the greatest height of 1.893 m, the measured value was 10.043 m/s^2 , corresponding to a 2.354% error compared with the standard 9.8 m/s^2 . As drop height decreased, the error increased, reaching 36.741% at 1.206 m. This trend suggests that longer fall times minimize relative error, supporting our prediction that the device would achieve higher accuracy at greater heights.

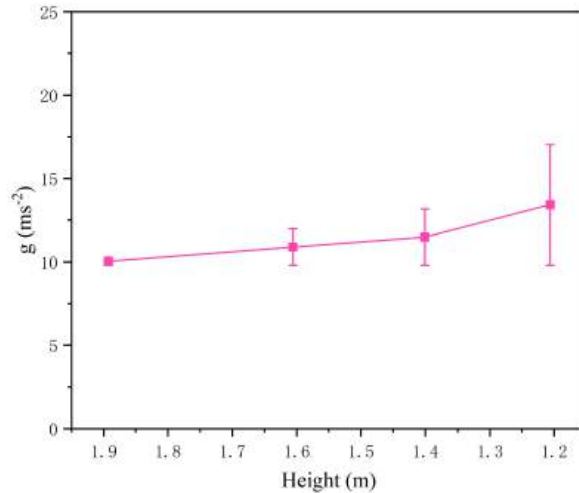


Figure 3. Gravitational acceleration error at different heights.

3.2 Compare the g with two different methods

From the height of 1.893 m, the sphere was dropped to compare the measure of g using manual timing and electromagnetic triggered auto-timing. Using formulas (4) and (5), the calculated values of g and the δ were 10.583 ms^{-2} and 7.980%, respectively. The results indicated that manual timing has larger fluctuations and bigger errors, while the electromagnetic triggered auto-timing method demonstrates stronger stability and has smaller errors shown in Figure 4. This is because manual timing introduces significant and highly random manual errors, often much larger than experimental errors.

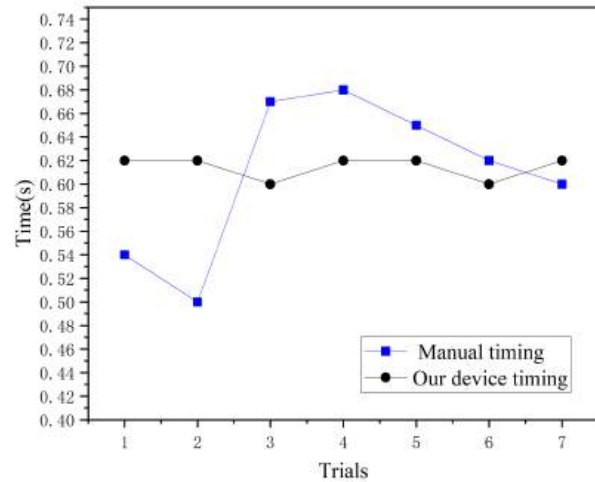


Figure 4. Comparison of the sphere's fall times measured by the two methods.

Our hypothesis was supported: the auto-timing device maintained percentage errors under 5% at optimal height, and repeatability exceeded 98%. This demonstrates that low-cost electromagnetic circuits can meaningfully improve accuracy in gravitational acceleration measurements. Therefore, this device offers considerable advantages over conventional methods. Experimental results indicated that the device could measure gravitational acceleration with reasonable accuracy, validating its effectiveness as a tool for education and research. Furthermore, since its knowledge base is grounded in high school physics content, this device facilitates demonstration and practice in classroom teaching. The successful integration of physics and electronics highlights the potential of interdisciplinary solutions in physics experiments.

4. Conclusion

In this experiment, we designed and built an electromagnetic triggered auto-timing device for measuring gravitational acceleration. By using commonly available laboratory materials, an integrated g testing system was realized, significantly reducing large errors caused by manual timing. The experimental data demonstrated greater stability, with an error of only 2.371%. This device innovatively combines fundamental physical principles with electronic engineering techniques, making it easy to operate. Experimental results show that the device can measure gravitational acceleration with reasonable accuracy, validating its effectiveness as a tool for education and research. Furthermore, since the knowledge base is grounded in high school physics content, it is convenient for demonstration and practice in classroom teaching. The successful integration of physics and electronics highlights the potential of interdisciplinary solutions in physics experiments.

However, limitations still exist. First, since the sphere experiment is conducted at a height of 1.893 m in the air, external factors such as turbulent airflow may cause inaccuracies in the results. To ensure smooth operation, this device is better suited for use in rooms without external airflow disturbances. Additionally, slight timing delays due to circuit response may introduce

small systematic errors. Future improvements may involve higher-precision timing devices. Overall, this apparatus not only provides a reliable testing method but also encourages students to engage in hands-on learning and creatively solve experimental physics problems.

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Gram-Negative Bacteria: Potential Method of Antibiotic Resistance Using Lactic Acid Bacteria and Chloramphenicol By Suri Ahn

Abstract

The purpose of this study is to investigate a solution of antibiotic resistance through a combination of lactic acid bacteria and chloramphenicol will help *P. fluorescens* and *E. coli* be more resistant. Past literature has studied solutions against antibiotic resistance because antibiotic resistance, especially in Gram-negative bacteria, has higher mortality rates and causes dangerous infections in the body. Many researchers have studied the benefits of chloramphenicol, an antibiotic, and the potential for using bacteriocin-producing lactic acid bacteria. However, there is a gap in research about whether a combination would be effective against the Gram-negative bacteria. A mixed method experimental method was conducted with control groups and experimental groups, which included the antibiotic and zone of inhibition. Data was collected through measurements of the diameter of the zone of inhibitions and pictures of the Mueller-Hinton Agar plate. The diameter of the zone of inhibitions were compared between the group with a combination and the group with just the antibiotic. There was a larger diameter for the combination in both *E. coli* and *P. fluorescens*. Therefore, the conclusion can be made that the use of chloramphenicol is more effective than the combination of chloramphenicol and lactic acid bacteria. However, there were limitations of no variability of the data due to the use of one sample size. Future research can include multiple trials for each treatment to ensure zones of inhibition values are accurate. The implications of this are that researchers, medical professionals, and patients can look towards more methods other than combination efforts.

Keywords Antibiotic Resistance, Gram-negative bacteria, Combination therapy, Antibacterial activity, Public health microbiology

Introduction

Antibiotic resistance is rising as a global health issue and a danger to our society. Resistance reduces the effectiveness of antibiotics, making disease and bacterial infections difficult to treat. Timothy R Walsh, Ana C Gales, Ramanan Laxminarayan, and Philippa C Dodd emphasize that antibiotic resistance is listed as one of the top 10 health threats in recent years. In 2019, resistance contributed to 4.95 million deaths – surpassing those caused by malaria, tuberculosis, and HIV/AIDS (Walsh et al. 1). Once found as one of the greatest discoveries to the field of medicine, antibiotics are becoming less competent due to mutations, genetic systems in bacteria that combat antibiotics, overuse of medications, and the lack of new drug developments to keep up with the emerging issues. When resistance in an antibiotic occurs, the target of the antibiotic action is shielded and treatment cannot be as effective (Komolafe et al. 2).

Unfortunately, this health issue is growing especially in developing countries and low income areas. In turn, there is a high demand for antibiotics or therapeutic treatments to improve patient care needs. Many companies have shifted their focus and abandoned antibiotic research

and the need to develop new antibiotics. Due to this abandonment, antibiotic resistance will increase and may be projected to lead to 10 million deaths by 2050 (Uddin et al. 1).

Literature Review

Issue of Antibiotic Resistance

Numerous authors who have studied antibiotic resistance stressed the dangers to society. A study by Muteeb and his coauthors provides background information of antibiotic resistance, explaining how a high concentration of advanced antibiotics caused a growth of bacteria to surge that were antibiotic resistant. In other words, bacteria have become better at resisting antibiotics through inactivating the antibiotics' cell walls, making infections harder to treat (Muteeb et al. 3). Antibiotic resistance has become particularly pressing with multidrug resistance, which occurs when bacteria become unaffected by multiple antibiotics. Infections caused by multidrug resistant bacteria contribute to high mortality rates as they are troublesome to cure, making people more prone to dangerous illnesses. The problem is not limited to specific groups as antibiotic resistant infections can affect anyone regardless of age, gender, or health, showing the wide range of individuals multidrug resistant bacteria can impact.

One consequence of antibiotic resistance that has caused attention are superbugs which are "microorganisms that are resistant to antimicrobials" (Muteeb et al. 3). These superbugs pose a threat to public health due to its difficulty in standard antibiotics. An example is *Pseudomonas aeruginosa*, a known multidrug resistant bacterium vital in the medical field. According to researchers Salam, Al-Amin, and Pawar, superbugs are germs "that have shown resistance to antimicrobial agents used to treat them" (Salam et al. 2). Currently, there is little treatment for superbug infections due to high treatment costs. In many cases, superbugs cause patients to have extended hospital stays, also adding to financial trouble. Hence, superbugs can make infections harder to control and more dangerous in healthcare settings. Authors Muteeb and Salam build the argument that superbugs and multidrug resistant bacteria is a major consequence that urges the healthcare community of the problems with antibiotic resistance.

Previous Methods

Researchers in past studies have been working on ways and new methods to reduce antibiotic resistance. One method, presented by Konwar and his three coauthors in *Current Microbiology*, used special proteins called antimicrobial peptides to weaken the bacteria's defenses and make the bacteria easier to treat. They also utilized efflux pump inhibitors—molecules that stop bacteria from pushing out antibiotics—making treatment effective. Nonetheless, the researchers point out the "high production costs compared to conventional antibiotics," (Konwar et al, 5). These limitations show that different possibilities should be considered to have an inexpensive and efficient approach. Considering alternatives, Roberta J Worthington and Christian Melander introduce combination therapy where a combination of two or more antimicrobial drugs are used during treatment. Despite this method being used frequently

in hospitals, there are chances of drug-drug interactions that cause issues to effectively target the bacteria (Worthington and Melander 2). Another study furthers the consequences of combination techniques as dual-drug delivery are “difficult to realize on large-scale clinical applications in terms of synthesis process and cost,” (Gong et al. 14). That is, a combination of two drugs may be problematic to produce on a large scale with cost issues. Together, these studies show that despite viable options of peptides, efflux pump inhibitors, and drug combinations, there is a need for a cost-effective solution to inhibit antibiotic resistance.

Gram-Negative Bacteria

The goal of the experiment is to focus on a specific multidrug resistant bacteria type: Gram-negative bacteria. While this study focuses on Gram-negative bacteria, Gram-positive is another type of bacteria that are similar in name, but not by nature. Zeinab Breijyeh, Buthaina Jubeh, and Rafik Karaman define Gram-negative bacteria as having three layers: the outer membrane, cell wall, and inner membrane. The outer membrane is a crucial aspect in resistance because antibiotics must pass through this membrane to reach the inside of the bacteria and target the harmful areas (Breijyeh et al. 3). Gram-positive bacteria do not have an outer membrane, making this type of bacteria easier to target. Changes to this layer can result in differences of resistance as Exner and his coauthors note. Exner mentions that since Gram-positive lacks the outer membrane, it is less resistant than Gram-negative, leading to the conclusion that Gram-negative is in more need of research and solutions (Exner et al. 2). Furthering this discussion, the study provides examples of the *Pseudomonas* species and *Escherichia coli*, which are known to be Gram-negative, multidrug resistant, and vital in research. Collectively, these research pieces underscore the need to develop treatments especially in Gram-negative and provides justification to use Gram-negative instead of Gram-positive bacteria.

Throughout literature, Gram-negative bacteria are also considered as dangerous and harmful. Dettori et al. in *Current Opinion in Critical Care* calls attention to Gram-negative bacteria’s association with severe nosocomial infections that include bloodstream infections and pneumonia (Dettori et al. 439). Gram-negative causes the most serious healthcare infections, affecting patients around the world. Sharmilla Devi and coauthors agree with the issue by noting Gram-negative bacteria infections increase mortality rates. They highlight the growing concern for therapeutic strategies as “there are very few effective antibiotics against these infections” (Devi et al. 7). From these sources, past literature stresses the concern of Gram-negative bacteria, and its harmful effects that influence public health.

As Exner and coauthors pointed out, *Pseudomonas* species is one of the most researched gram-negative bacteria in its relation to medicine (Exner et al. 3). While many researchers have focused on *Pseudomonas aeruginosa* for its clinical importance, *Pseudomonas fluorescens* is not as well researched, despite its strong correlation to bloodstream, skin, and urinary infections (Silverio et al. 985). This bacterium also relates to environmental issues such as drinking contaminated water in medical procedures. On the other hand, *E. coli* is more researched in medical studies. For example, the CDC provided extensive studies on *Escherichia coli* as a

common bacterium of humans and animals (Collins et al.). Like *Pseudomonas fluorescens*, *E. coli* can cause urinary infections and gastroenteritis and both bacteria need to be paid more attention too for the protection of the community.

Potential New Method of Antibiotic and Bacteriocins

A key part of the experiment is testing an antibiotic on both *P. fluorescens* and *E. coli* to check for resistance or sensitivity. Previous studies have tested many antibiotics to find alternative treatment options. In one study, Trivedi and his coauthors tested *Pseudomonas fluorescens* with kanamycin, tetracycline, ceftazidime, and chloramphenicol and its antibiotic susceptibility. They found that chloramphenicol caused high sensitivity in *P. fluorescens*, indicating that the antibiotic is effective against the bacteria (Trivedi et al. 5). On the same note, Mulugeta Kibret and Berhanu Abera, researchers at Bahar Dar University, conducted a similar experiment of antibiotic susceptibility on *E. coli*. Unlike other studies, Kibret and Abera focused on *E. coli* in clinical samples from patients as it is a major cause of human body infections. Through a Mueller-Hinton agar plate test, they found that chloramphenicol was one of the most effective antimicrobials against *E. coli*. Together, these authors show that chloramphenicol is sensitive and effective to both *P. fluorescens* and *E. coli*.

However, this study aims to find a new way to target antibiotic resistance. One area of antibiotic resistance that is unresearched is combining bacteriocins with antibiotics. Bacteriocins are antimicrobial peptides that have been found effective against human diseases. Pawar and Tiwari reiterate bacteriocin-producing lactic acid bacteria as being effective through a past study of gut in mice, a study that may be mirrored in human bodies. These two authors concluded that lactic acid bacteria can target respiratory infections, infections that are related to Gram-negative bacteria, and *E. coli* diseases (Pawar and Tiwari 3). Lactic acid bacteria are also common probiotics found in the human body, pointing to a relation to both *P. fluorescens* and *E. coli* which are similarly found in the gut and multiple areas of the body. Alakomi and his coauthors further support the use of lactic acid bacteria. As mentioned previously, Gram-negative has an outer membrane that makes it hard for antibiotics to penetrate. However, Alakomi's research found that lactic acid bacteria increase the outer membrane permeability of *E. coli* and *Pseudomonas* species, allowing bacteria to pass through this membrane. Lactic acid bacteria "functions as a permeabilizer of the gram-negative bacterial outer membrane" and acts like a "potentiator of the effects of other antimicrobial substances," (Alakomi et al. 2001). This permeabilizer function makes using lactic acid bacteria a promising way to fight antibiotic resistance because it makes the Gram-negative bacteria easier to target and treat. Past literature discovered bacteriocin-producing lactic acid bacteria as a potential to target infections made from *P. fluorescens* and *E. coli*.

Throughout literature, it is detected that antibiotic resistance is a challenging problem and an increasing danger to healthcare. The use of certain antibiotics, specifically chloramphenicol, with bacteriocin-producing lactic acid bacteria addresses a new strategy to help hospitals, patients, and medical research. There has been little research on combining an antibiotic and a

bacteriocin despite numerous authors researching both topics separately. This experimental study aims to fill this research gap by providing a new combination between chloramphenicol and lactic acid bacteria. The study aims to fill these gaps by answering the question: What effect would combining lactic acid bacteria and chloramphenicol be on resistance in *Pseudomonas fluorescens* and *Escherichia coli*? The leading hypothesis is that the combination of lactic acid and chloramphenicol will have the most sensitivity, therefore meaning it is more effective against both Gram-negative bacteria. Through the detailed experiment, it is determined whether the addition of lactic acid bacteria allows *P. fluorescens* and *E. coli* to be more resistant, filling research knowledge.

Method

Rationale

To discover whether a combination of lactic acid bacteria could allow a larger zone of inhibition for *Pseudomonas fluorescens* and *Escherichia coli*, I ran a mixed method experimental approach to determine resistant effects. The goal of the study is to explore a potential solution to antibiotic resistance in Gram-negative bacteria by combining chloramphenicol and lactic acid bacterium. A mixed method approach requires both quantitative and qualitative data which provides a visual and numerical representation to clearly identify whether a combination is more effective than the use of the antibiotic on its own. Quantitatively, the diameter of the zone of inhibition was measured in millimeters and qualitatively, pictures were taken of the clear area around the antibiotic. The clear area around the antibiotic is named the zone of inhibition which indicates where bacteria cannot grow. A larger diameter of the zone of inhibition means a bacterium is more sensitive to the antibiotic. The findings for zones of inhibitions will determine whether a combination can make the Gram-negative more resistant or sensitive. This method was chosen to clearly determine antimicrobial sensitivity and observe the effects of lactic acid bacteria efficiently through quantitative and qualitative analysis. A meta-analysis study will not produce the same findings as an experiment because *P. fluorescens* is less researched compared to *E. coli*, creating uneven results. Moreover, a meta-analysis is generalized across multiple studies and will not provide the results to specifically test a combination.

Before starting the experiment, there were many definitions to be known. An antibiotic is a medicine that can treat bacterial infections by stopping or killing bacteria. In this experiment, chloramphenicol is the antibiotic used because it has been proved effective for *P. fluorescens* and *E. coli*. Next, bacteriocins are antimicrobial peptides that are produced by bacteria to kill other bacteria. In this study, lactic acid bacteria acted as the bacteriocin because they can produce bacteriocins and other more commonly known bacteriocins were not available. The bacteria that will be implemented are known as Gram-negative bacteria defined by microorganisms that have high resistance to antibiotics due to its outer membrane. Specifically, *Pseudomonas fluorescens*, a Gram-negative and rod-shaped bacterium, and *Escherichia coli*, a bacillus that can cause food poisoning, were selected.

Because bacteria will be involved, safety will be a top priority. *P. fluorescens* and *E. coli* are nonpathogenic, but lab safety is still prioritized. Unfortunately, the strain IDs were not specified, but the samples were bought from Carolina Biological Supply. Before completing lab work, I washed my hands to prevent contamination and wore goggles. For supplies, I obtained a pipette to transfer my Gram-negative bacteria onto the Mueller-Hinton Agar plates, which are plates commonly used for antibiotic susceptibility tests due to their ability to diffuse the antibiotic and create a truer zone of inhibition. I also obtained an inoculation loop to spread the bacteria across the entire plate. Both tools were sterilized and clean from bacteria, eliminating potential for contamination. The tweezers, which were used to transfer the antibiotic to the Mueller-Hinton agar plates, were not initially sterilized and instead, a Bunsen burner was used to remove any excess particles. Between each transfer of the antibiotic, the tweezers were heated up from the Bunsen burner flame.

Bacterial Conditions

My research question aims to ask for the outcome of a combination of lactic bacteria and chloramphenicol on the Gram-negative bacteria, emphasizing whether lactic acid bacteria can create a change in the zone of inhibitions. So, I split up the two Gram-negative bacteria into four plates of *P. fluorescens* and four plates of *E. coli*. For the *E. coli*, the control groups were *E. coli* on its own and one with lactic acid bacteria. Control groups are necessary to show how the Gram-negative bacteria grows without interference and with the lactic acid bacteria compared to the addition of the antibiotic. The experimental groups consisted of one plate of *E. coli* with the treatment of chloramphenicol and the other with a combination of chloramphenicol and lactic acid bacteria. Both control and experimental groups were plated on Mueller-Hinton Agar plates. All in all, there are four plates inoculated with the *E. coli*. Likewise, *P. fluorescens* was inoculated in the same manner, with four plates and the same control and experimental groups. In total, there were eight dishes.

These trials were conducted to account for consistency between the two bacteria and to eliminate errors. To begin, around 0.25 mL of *E. coli* was measured with the pipette and used in four plates. With one inoculation loop, the bacteria were spread across the entire bottom of the plate. Then, with a new inoculation loop, lactic acid bacteria were also spread across the bottom in only two of the four plates. To note, the lactic acid bacteria test tube came as an agar, meaning it was solid and a pipette could not be used. Finally, with the sterile tweezers, one antibiotic was placed into the middle of two plates to analyze the zone of inhibition clearly. After the *E. coli* was completed, the same steps proceeded for the *P. fluorescens*. Once all the plates were finished, they were placed in two separate incubators due to temperature differences. *E. coli* was incubated at 37°C and *P. fluorescens* was incubated at 25°C. These degrees of temperatures are common in experiments because they allow each bacterium to grow effectively (Vimont et al., 2006).

To add on, only a single plate was used per treatment group. No replicates were performed, highlighting a limitation to assess experimental variability or draw statistical conclusions. Consequently, the findings from the bacterial conditions and setups should be

considered preliminary observations rather than definitive results. Another point to consider is that both lactic acid bacteria and pathogen concentrations were not quantified.

Quantification of Data

I checked the bacteria each day and recorded the zone of inhibition using a ruler for five days. The measurements that I collected only included the plates with the chloramphenicol because an antibiotic causes the zone of inhibitions. So, I used four plates out of the eight for my quantitative and qualitative analysis while the others are control groups with no zone of inhibitions. Bacteria can grow fast within one night, so only five days were measured to see if there was going to be any change in the zone of inhibitions. Using millimeters on the ruler, the distance from the center of the antibiotic to the edge of the clear circle of the zone of inhibition was measured. The data table below was used to keep track of the measurements.

Table 1: Data Table Used in Experiment

Bacteria	Day 1	Day 2	Day 3	Day 4	Day 5
E. coli + lactic acid bacteria + chloramphenicol					
E. coli + chloramphenicol					
P. fluorescens + lactic acid bacteria + chloramphenicol					
P. fluorescens + chloramphenicol					

However, this study includes limitations during the method section. One limitation is that I inoculated my plates on Friday and did my data collection on the following Monday. I could not collect data over the weekend and could not measure each day of the growth, so it is unknown whether the bacteria grew within the day or gradually over the weekend. On Monday, the zone of inhibitions for the four plates had stayed the same for the next five days. The gap in observation and data collection may have caused a loss in measuring the zone of inhibition growth. This may have led to bacterial overgrowth and antibiotic degradation due to the 72-hour gap of measuring the zone of inhibitions. Additionally, there is a limitation of using the lactic acid bacteria as the bacteriocin. Lactic acid bacteria are bacteriocin-producing, but not all of them do, leading to suspicions on whether the growth was more related to the bacterial contents rather than the bacteriocins. The lactic acid bacteria were not confirmed to be bacteriocin producing, advancing the limitation on whether the antimicrobial growth was due to other factors in the study. To note, the zone of inhibitions for both plates of *Pseudomonas fluorescens* were not a perfect circular

shape and had an uneven diameter, making it difficult to measure. From this, the average of the two different lengths of zone of inhibitions was calculated which may not be as accurate to its true measurement. There were most likely issues with inoculation and not inoculating the bacteria all over the plate before transferring the antibiotic in the middle. With gaps of clear spots on the plate, it can be mistaken for a zone of inhibition when it may not be related to the antimicrobial effectiveness.

Results

The experiment was conducted for five days. I inoculated on January 24th, 2025, and I finished data collection on January 30th, 2025. Qualitative data in the form of photographs was taken on the last day of data collection. Quantitative data, particularly the length of the zone of inhibitions, was collected throughout this period. These measurements are summarized in Table 2 below which shows the diameter of the zone of inhibition in millimeters for the plates that did include the chloramphenicol.

Table 2: Diameter of Zone of Inhibitions in Millimeters

Bacteria with Treatment	Day 1	Day 2	Day 3	Day 4	Day 5
E. coli+ lactic acid bacteria + chloramphenicol	18 mm	18 mm	18 mm	18 mm	18 mm
E. coli+ chloramphenicol	24 mm	24 mm	24 mm	24 mm	24 mm
P. fluorescens+ lactic acid bacteria + chloramphenicol	7 mm	7 mm	7 mm	7 mm	7 mm
P. fluorescens+ chloramphenicol	9 mm	9 mm	9 mm	9 mm	9 mm

As Table 2 shows, the zone of inhibition measurements did not change over time and remained constant from Day 1 to Day 5 for all treatments, indicating that the bacteria grew in the absence of data collection over the weekend. These constant measurements over the data collection period suggests that the bacteria had a longer period of growth over the weekend when I was unable to collect data. It is important to note that the data collection only occurred during school hours and there were no measurements over the weekend, as mentioned.

With photographs taken on Day 5, the study conducted a qualitative analysis to note any changes over time. This can be shown in Figure 1 and 2, which photographs the Mueller-Hinton Agar plates.



Figure 1: Photos of *Pseudomonas fluorescens* Plates Day 5

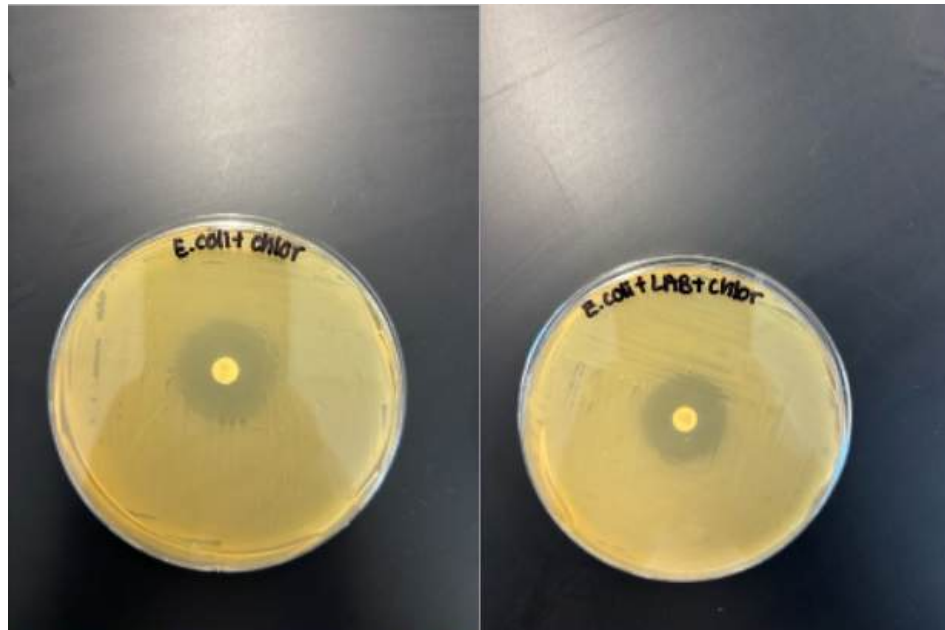


Figure 2: Photos of *Escherichia coli* Plates Day 5

Over each day, observations were written down and it was observed that the zone of inhibition for *Pseudomonas fluorescens* was extremely small and uneven, highlighting a previously mentioned limitation in the experimental design. On the other hand, *Escherichia coli* showed a clear response to the antimicrobial and had a much larger zone of inhibition that could be easily measured. These results suggest that chloramphenicol was more effective in limiting *E. coli* growth compared to the *P. fluorescens* as there was clear sensitivity shown. Note that Figure

1 and Figure 2 are endpoint measurements, only taken on the last day of the time measurements due to the fact that the plates looked identical each day.

Analysis

The zone of inhibition of all the plates represents the area where no bacterial growth occurs, indicating an effectiveness of the antimicrobial agent. The results of this study lay a solid foundation for further investigation into the potential of combination treatments or discoveries of new methods that will combat antibiotic resistance. The following graph in Figure 3 illustrates the differences in bacterial response to the treatment, comparing whether a combination of lactic acid bacteria and chloramphenicol is more effective than just the chloramphenicol alone.

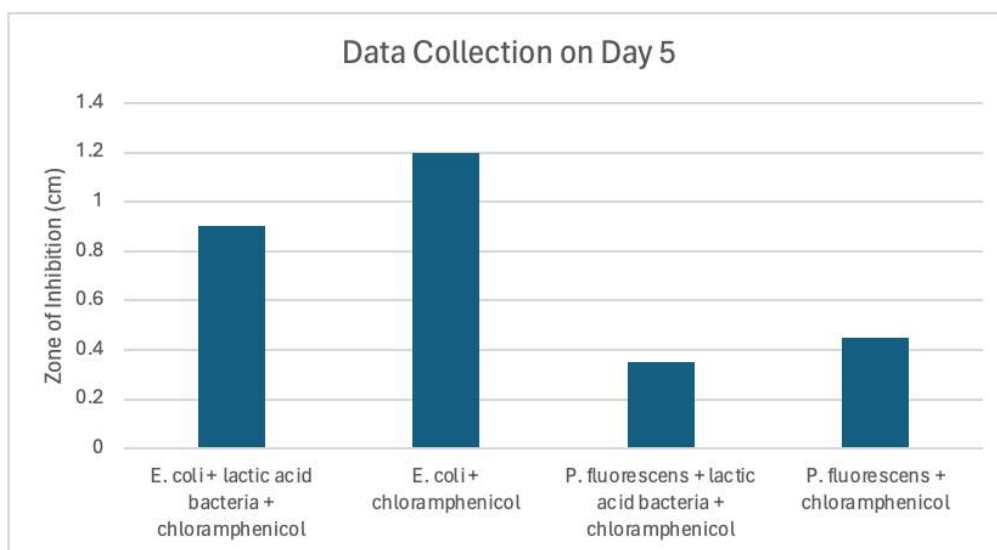


Figure 3: Bar Graph of Zone of Inhibition Measurements from Day 5

Analysis of Combination Treatment versus Antibiotic Alone

A larger measurement in the zone of inhibition indicates more effectiveness against the bacteria. In this experiment, both *Escherichia coli* and *Pseudomonas fluorescens* treated with the chloramphenicol alone demonstrated greater zones of inhibition compared to the combination of lactic acid bacteria and chloramphenicol. *E. coli* and chloramphenicol produced an inhibition of 1.2 millimeters, while the combination measured 0.9 millimeters. Similarly, *P. fluorescens* and chloramphenicol have a zone of inhibition of 0.45 millimeters, whereas the combination measures 0.35 millimeters. This outcome contrasts with findings from previous authors in literature that suggested bacteriocins could enhance antimicrobial efficacy. Specifically, these findings did not align with the idea that Alakomi and his coauthors claim with lactic acid bacteria affecting the outer membrane in *E. coli* and *Pseudomonas* species (Alakomi et al. 2001). The difference between the combination treatment and the antibiotic on its own could be due to the concentration of lactic acid bacteria as the experiment may have needed more or less of lactic acid bacteria to create a larger zone of inhibition.

Conclusion

This study aimed to answer the research question: What effect would combining lactic acid bacteria and chloramphenicol be on resistance in *Pseudomonas fluorescens* and *Escherichia coli*? To investigate this question, an experiment was conducted where the two Gram-negative bacteria each plated in four conditions: on its own, one with chloramphenicol, one with lactic acid bacteria, and one with a combination of the chloramphenicol and lactic acid bacteria. The results indicated that *E. coli* with the chloramphenicol has the highest antimicrobial effectiveness, with its largest zone of inhibition. Furthermore, the combination demonstrated reduced efficacy compared to the antibiotic alone, showing that a combination method is not an optimal strategy to combat antimicrobial resistance. Although there is a disagreement in efficacy of a combination method, these findings support the hypothesis of the use of chloramphenicol and its effectiveness against Gram-negative bacteria as there was a large zone of inhibition in both *P. fluorescens* and *E. coli*. Trivedi and his coauthors align with the hypothesis as they state chloramphenicol is one of the more capable antibiotics against Gram-negative bacteria.

However, my overall hypothesis that lactic acid bacteria and bacteriocins are effective against Gram-negative bacteria is not consistent with my findings as there was an opposite effect. This does not support Pawar and Tiwari's findings that lactic acid bacteria can target *E. coli* and respiratory infections, which are infections associated with the *Pseudomonas* species. Additionally, the study by Alakomi and coauthors who supported the use of lactic acid because it affects the outer membrane of *P. fluorescens* and *E. coli* does not align with my study. My findings have revealed Gram-negative bacteria appeared less susceptible in the presence of the lactic acid bacteria, though replication and further testing are needed to confirm this pattern.

Discussion

Implications

The results of the study provide useful information to stakeholders addressing the global challenge of antibiotic resistance. The results provide doctors, patients, and researchers more insight regarding differences in *Escherichia coli* compared to *Pseudomonas fluorescens*, shedding light on the varying susceptibility of these Gram-negative bacteria to different treatments. In this case, using just the chloramphenicol found to be more effective against both Gram-negative bacteria, suggesting that a combination of bacteriocins and chloramphenicol may not be a viable method for enhancing antibiotic efficacy. This insight can contribute to ongoing knowledge on treatment strategies, inform medical professions towards more effective approaches while discouraging potential for using combinations.

Limitations

After analyzing my data, an important limitation rose. For each type of dish whether it was a combination or just the antibiotic, it was only a sample size of one. In simple terms, I only had one sample of an *E. coli* with lactic acid bacteria and chloramphenicol, one sample of *E. coli*

with chloramphenicol, etc. Because there was only one sample size, it prohibited me from analyzing a variation between different trials. Having only one trial conducted may leave uncertainty within my data and whether the zone of inhibition measurements will be the same each time. This limitation caused another obstacle in my analysis. Due to the zone of inhibitions' lack of trials for each plate I inoculated, there was no variation in the data. In statistical terms, no variability means there is no standard deviation to analyze, prohibiting me from using a statistical inference procedure. I was unable to conduct an ANOVA test, an analysis for variance test, which did not allow me to estimate uncertainty from sample to sample. Although this limitation exists, it makes me more confident in my experiment and that the zone of inhibitions is accurate because there was no variability. Moreover, lactic acid bacteria viability and bacteriocin production could not be confirmed in the study, leading to weaker results.

Future Research

While this study fills a gap in current research and understanding of antimicrobial resistance mechanisms in Gram-negative bacteria, future research is warranted to expand on these findings. Future experiments should incorporate a longer period to see if any observed changes would happen eventually. One could conduct an experiment that spans for multiple weeks with more trials and more Mueller-Hinton Agar plates. For example, instead of one trial to test the effectiveness of a lactic acid bacteria and chloramphenicol, there can be at least three trials to see any changes in the zone of inhibition from sample to sample. This would test for variability that my experiment did not include. Other avenues for research can be using multiple bacteriocins and antibiotics rather than just testing lactic acid bacteria and chloramphenicol. Having more research into different combinations and testing which combination was more effective would be useful in finding a potential solution. Also, future studies should conduct a viability check of lactic acid bacteria activity and mention whether bacteriocin production was tested. These ideas for future research will enhance health professionals' efforts to develop effective strategies towards a greater health community.

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The Effect of Weekly Participation in Basketball on Sleep Quality among Autistic Children

By Jennifer Xue

Abstract

Poor sleep quality is a common issue among children with autism, often contributing to behavioral issues and reduced cognitive functioning (Tudor). Because of the ongoing sleep issues, studies regarding autistic children have analyzed what could help increase the quality of sleep for this demographic of people. This qualitative study will analyze what the effect of weekly participation in basketball is on the sleep quality in autistic children. Five interviews were conducted with parents of the autistic children who attended the weekly basketball practices. Each interview was consistent with the others, using the same questions. The answers to the questions were then split into different sections that were centered around specific themes. These themes corresponded to the wide variety of ways people describe sleep quality. This qualitative study explores whether weekly participation in basketball positively influences sleep quality in autistic children, with the goal of identifying a potentially effective and holistic intervention to support their well-being.

Introduction

Only a few studies regarding sleep and autistic children have been conducted in the past. Most existing research about children with autism revolves around social aspects, emotion regulation, and motor skills in contrast to sleep quality issues (Tudor). Sleep issues are often under-recognized by research about children with autism. Poor sleep can make behavior challenges even worse, reduce learning, and increase the stress of parents of autistic children according to multiple sources across Google Scholar. Through conducting 5 interviews with the parents of autistic children aged 5-15 at a local non-profit organization and reading existing research online, this article examines the likelihood that participating in basketball weekly increases the sleep quality of autistic athletes.

Literature Review

Research regarding autistic children across Google Scholar has concluded that regular, long-term exercise leads to significant improvements in physical health, social relationships, and more. However, differences in intervention type and intensity across studies made it difficult to pinpoint which specific activities are most effective. Further research analyzing the area of sleep quality uncovered that children and adolescents with autism spectrum disorder experience sleep disorders at significantly higher rates (40–80%) compared to typically developing peers (Tudor). There are frequent abnormalities in REM sleep among children with ASD. The effects of sport and physical activity interventions have consistent positive impacts across many domains, emphasizing improvements in all sorts of areas, although nonspecific to sleep have thoroughly been analyzed.

Several studies have demonstrated the unique benefits of exercise for children and adolescents with ASD. For example, findings show that “long-term, regular, chronic exercise is beneficial for children and adolescents with autism, particularly in the area of social skills” (Bernabei). In addition, sport and physical activity interventions have positive effects on cognitive aspects as well as decreasing some prominent symptoms of ASD. This suggests that individuals with autism can benefit from sports across a wide range of physical, psychological, and social domains.

In addition to the role of exercise, research on sleep quality among children with ASD (autistic spectrum disorder) has uncovered consistently higher rates of sleep disturbance compared to typically developing peers. Studies estimate that “children and adolescents with ASD suffer from sleep problems, particularly insomnia, at a higher rate than typically developing (TD) children, ranging from 40% to 80%” (Tudor). Many of these difficulties are tied to abnormalities in REM sleep, which are observed more frequently among individuals with autism according to the same source. Treatment strategies for these sleep challenges often focus on behavioral interventions: “implementation of no pharmacotherapeutic measures such as bedtime routines and sleep-wise approach are the mainstay of management” (Tudor).

The literature suggests that sport and physical activity interventions hold promise for improving social, physical, and cognitive functioning in children and adolescents with ASD.

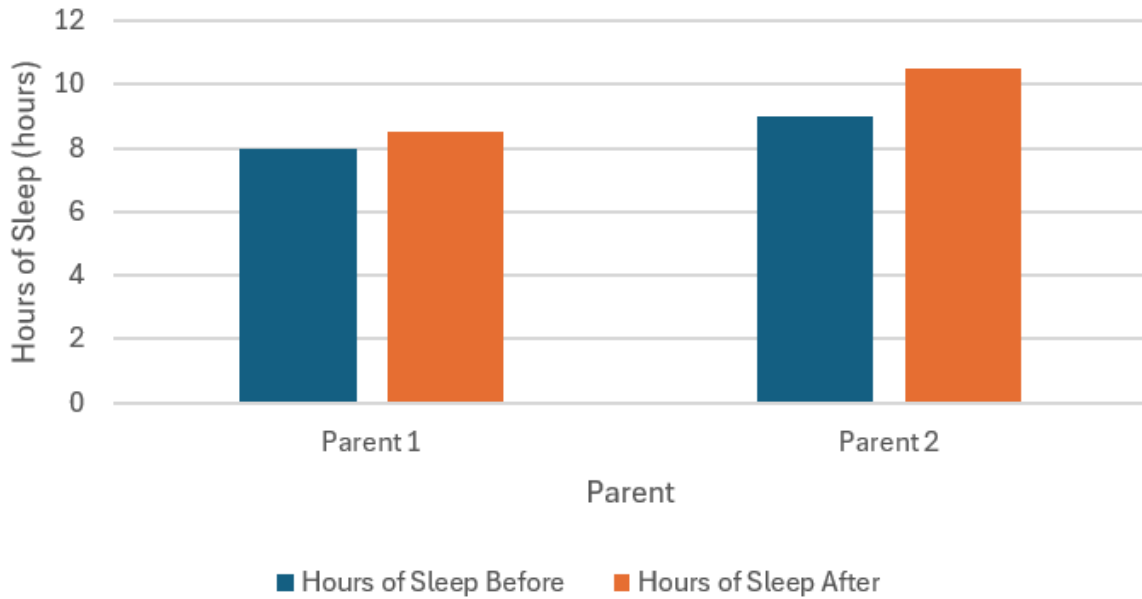
Methods

For this study, I interviewed five parents of autistic children at a non-profit organization dedicated to engaging autistic youth with sports. I visited a basketball practice at the local non-profit that specializes in helping children with autism engage in different activities that they enjoy. The basketball team meets every Saturday for two hours. I asked each set of caregivers two simple questions: how they would describe their child’s sleep quality on a daily basis and how they would describe their child’s sleep quality after participating in basketball practice. The parents’ answers were categorized into different themes including the number of hours of sleep, the amount of time it took to fall asleep, and potentially the presence of nightmares.

Survey Results

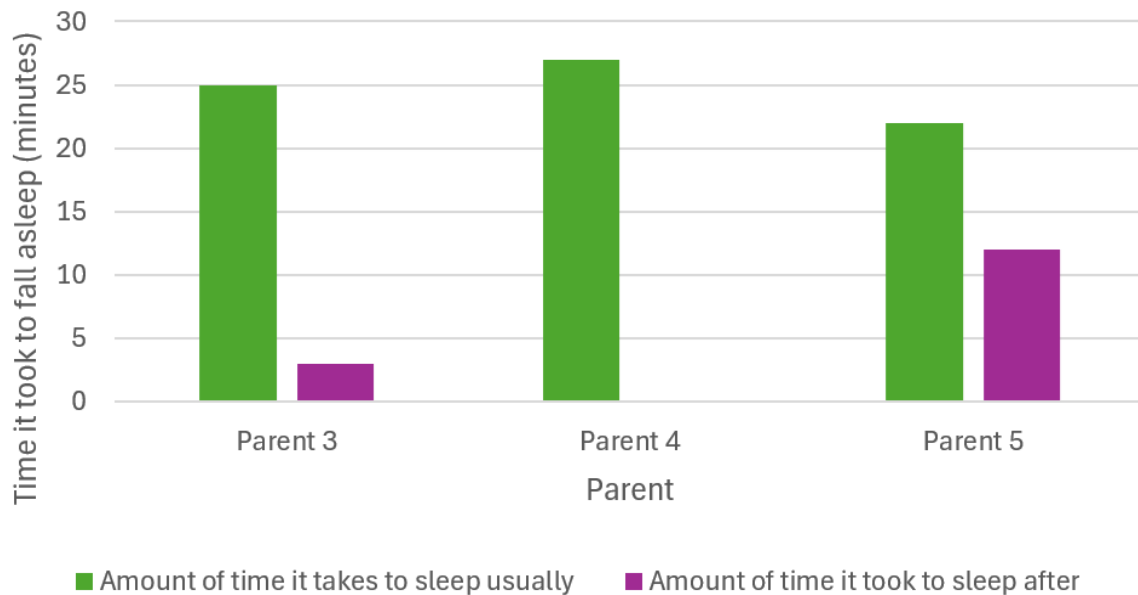
The two major themes that were present in the five interviews conducted with the parents of autistic children were sleep length and the amount of time it took to fall asleep for an athlete. Two parents reported that their child slept around 1 to 2 hours more than that of a typical day. One parent said their child slept earlier due to being more tired after the practice while the second parent said that their child woke up later than the previous day.

Parent 1 and Parent 2 Hours of Sleep



The majority of the parents (the other three) all reported that the amount of sleep their child got didn't necessarily change after participating in basketball practice. However, the amount of time it took for their child to fall asleep after getting into bed was significantly shorter.

Parent 3, 4, and 5 Time to Sleep



Out of those three parents, one parent reported that their child fell asleep almost immediately after getting in bed after sports practice compared to a normal day, in which they

would usually take twenty to thirty minutes. Another parent reported that their child fell asleep within ten minutes of getting into bed compared to the usual twenty to twenty-five minutes. The last parent interviewed said that their child took around fifteen minutes to fall asleep in contrast to the usual twenty to twenty-five minutes.

Despite some variations between how their child's sleep was affected, all of the parents responded positively regarding the participation of weekly basketball when asked to compare against a normal day. None of the parents noticed any noticeable difference in the child's dreams. As these interviews were conducted as a casual conversation, one of the parents reported that weekly basketball practice not only helped their child sleep but also seemed to allow their child to wake up happier and more enthusiastic. This was not categorized into one of the themes as it was not directly connected to sleep quality, but it could've been a result of sleeping longer.

Analysis/Discussion

Like current and former research conducted by researchers focused on autism, sports, and sleep, the results found through this qualitative analysis also displayed how participation in sports has an overall positive effect on a child with autism's life. In this case, the autistic children that participated in weekly basketball practices at a specific non-profit organization all either slept for a longer period or took less time to fall asleep. These results respond to the existing research regarding prominent sleep issues with children with ASD by presenting weekly participation in a certain sport to potentially be a way to improve sleep in addition to previous methods like a strict sleep schedule. Some previous research conducted by Devani and Hedge did also report that almost 40-80% of children and adolescents with ASD suffered from insomnia, which the weekly participation in basketball did seem to counteract as the amount of time to fall asleep was seen to decrease extremely.

Limitations

There were some limitations in this analysis, however. The number of hours of sleep each of the autistic children slept is not a clear indicator of overall sleep quality as it could be affected by their schedule the following day. As the interviews were conducted in casual conversation, some parents only commented on the length of their child's sleep increasing. We can't conclude an effect of participation in basketball on their sleep length because their usual sleep schedule might have been dictated from summer camps, classes, etc. As for the number of minutes a child took to fall asleep, this could've been dictated by the amount of sleep received the previous night. The child could've had a rough night of sleep the day before and coincidentally happened to be extremely tired the night of the basketball practice. Although the limitations prevent us from drawing a faultless conclusion, because the same pattern was observed between multiple children, we can safely assume that a positive connection between the weekly participation in basketball and each child's sleep quality exists. Hence, this was an appropriate analysis to take a general conclusion despite possible shortcomings with the methods.

Conclusion

This qualitative study suggests that weekly participation in basketball may have a positive influence on the sleep quality of children with autism, particularly by reducing the time it takes them to fall asleep and, in some cases, extending sleep duration. While the small sample size and informal nature of the interviews limit the generalizability of these findings, the consistent reports from parents point to a meaningful connection between structured physical activity and improved sleep outcomes. Future studies with larger participant groups, controlled conditions, and more precise sleep measurements are needed to confirm and expand upon these findings. Nonetheless, this study provides preliminary evidence that basketball supports both the sleep quality of autistic children.

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Do Brain-Inspired Spiking Neural Networks Outperform Other Deep Learning Models in EEG Seizure Prediction? By Nam Nguyen

Abstract

The development of robust seizure prediction models and devices is critical for advancing clinical applications in epilepsy care. In this study, we investigate whether biologically inspired Spiking Neural Networks (SNNs), which mimic neuronal firing mechanisms, offer advantages over conventional deep learning architectures for EEG-based seizure prediction. Using the CHB-MIT dataset, we compare the performance of five models—LSTM, CNN, SNN, GNN, and Transformer—given the same preprocessing and training pipeline. These models are trained on around 23 hours of CHB-MIT data and evaluated using accuracy, sensitivity, specificity, and ROC AUC metrics. Our results show that SNNs delivered robust and consistent performance, achieving higher accuracy, specificity, and ROC AUC scores than LSTM, CNN, and Transformer models, but comparable to GNNs. GNNs achieved the highest average sensitivity, which is critical for clinical settings. While SNNs demonstrated strong overall reliability and highlighted the potential of brain-inspired architectures for advancing seizure prediction systems, they still require further refinement to surpass the best-performing conventional models.

Keywords deep learning, neural networks, signal processing, EEG, seizure prediction

I. Introduction

Neural signal processing

Neural signals are electrophysiological signals generated from the activity of neurons, which facilitate information transmission across the nervous system. They are often recorded using techniques such as electroencephalogram (EEG), magnetoencephalography (MEG), and functional magnetic resonance imaging (fMRI). These neural signals are characterized by high-dimensionality, nonstationarity, and noisiness. Because of this, they require techniques such as filtering, spectral analysis, and feature extraction to remove artifacts and obtain meaningful patterns and information (Chaddad et al. 6434; Govil, Yao, and Borao).

Recently, AI-based techniques have been employed to process neural signals, achieving great performance in applications such as seizure detection, movement intention decoding, and speech synthesis from neural activity (Saeidi et al. 1525). This approach will be explored in this study.

Epilepsy & seizure prediction via EEG signals

Epilepsy is a neurological disorder that affects around 50 million people worldwide, characterized by epileptic seizures, which are periods of involuntary muscle contractions and convulsions as a result of excessive electrical discharges in the brain. People affected by epilepsy have more physical problems, psychological conditions, and have up to three times higher risk of

premature death than the general population (World Health Organization). Prediction of epilepsy using EEG data involves learning and modeling complex, time-dependent neural activity patterns to forecast brain states. Deep learning architectures offer a compelling direction for exploration and research. Their performance in complex, nonlinear data is well-suited for capturing and processing EEG signals. By advancing these architectures and the principles that they are built upon, we are able to develop practical healthcare applications.

II. Literature Review

Neural signal processing

Work done on neural signal processing utilizes both classical signal processing techniques and AI-based methods. Various filtering techniques, such as multi-channel Wiener filters (MWF), FIR/IIR filters, and Butterworth filters, are used to remove artifacts from noisy signals (Singh and Malhotra 2405-2418; Chaddad et al. 6434). Feature extraction methods are then used to extract valuable information from the signal. Wavelet transforms, empirical mode decomposition, and Fourier transform variants are used for frequency-domain and multi-resolution analysis (Lee et al. 1965 ; Hussein, Lee, and Ward 1551 ; Alickovic, Kevric, and Subasi 94-102). Methods such as approximate entropy, fast Fourier transform (FFT), and discrete wavelet transforms (DWT) have also been utilized in biomedical neural signal processing systems, such as EEG seizure detection systems (Vangal and Riske). Neural signal processing pipelines can be built entirely on these classical signal processing techniques or incorporate machine learning and deep learning models down the pipeline. These models include convolutional neural networks (CNNs) (Rakhmatulin et al. 877), long short-term memory (LSTMs) (Kumar, Sharma, and Tsunoda 10011), and transformers (Wang et al.), which have demonstrated superior performance to traditional processing techniques across a wide range of neural signal processing tasks.

EEG seizure prediction

Many studies have been done on seizure prediction using EEG data and deep learning, with most of them framing the problem as a binary classification task with interictal and preictal periods as labels. Wu et al., Tsiouris et al., and Chambers et al. aim to learn the temporal dependencies of neural activity in EEG signals and anticipate seizures by leveraging long short-term memory (LSTM) models. Building on this, Lee et al. , Liu et al. , and Bhattacharya used variations of the LSTM model, namely the Resnet-LSTM, BiLSTM, and CNN-LSTM, to better capture complex bidirectional and spatio-temporal dependencies. Truong et al., Khan et al., and Usman et al. used a convolutional neural network (CNN) model to model spatio-temporal dependencies in EEG signals, eliminating the need for handcrafted feature extraction.

Problem Statement & Purpose

The purpose of this study is to explore whether brain-inspired Spiking Neural Networks (SNNs) offer advantages over conventional deep learning architectures for seizure prediction. We formulated our question based on the fact that SNNs are explicitly designed to process

information in a way that resembles how the brain encodes and transmits signals, making them a natural candidate for tasks involving neuronal activity, such as EEG-based seizure prediction. We compare five architectures—LSTM, CNN, SNN, GNN, and Transformer using the same preprocessing pipeline, allowing us to isolate the role of model design in performance differences.

While these models are trained and tested on an EEG-based seizure prediction dataset, they have not yet been deployed or validated in real-world clinical environments. Due to limited computational resources, evaluation was restricted to the first 7 patients in the CHB-MIT dataset, which may affect generalizability. Furthermore, the use of a preprocessing pipeline rather than raw EEG input introduces additional constraints. These limitations should be addressed in future work.

III. Methods & Materials

Overview of architectures

**Where not specified, W represents the weight matrix, and b represents the bias*
Long Short-Term Memory (LSTM)

For an input sequence $x_t \in R^d$ at time t , the LSTM cell computes:

$$\begin{aligned} i_t &= \sigma(W_i x_t + U_i h_{t-1} + b_i) \\ f_t &= \sigma(W_f x_t + U_f h_{t-1} + b_f) \\ o_t &= \sigma(W_o x_t + U_o h_{t-1} + b_o) \\ \tilde{c}_t &= \tanh(W_c x_t + U_c h_{t-1} + b_c) \\ c_t &= f_t \odot c_{t-1} + i_t \odot \tilde{c}_t \\ h_t &= o_t \odot \tanh(c_t) \end{aligned}$$

Final output:

$$y = \sigma(W_2 \text{ReLU}(W_1 h_T + b_1) + b_2)$$

where:

- c_t is the updated cell state (the model's long-term memory).
- h_t is the updated hidden state (the model's working memory, used for output).
- f_t, i_t, o_t are the forget, input, and output gates that regulate information flow.
- c_{t-1} is the previous cell state.
- $\tilde{c}_t$ is the new candidate information to be added to the memory.

- $\odot$ denotes element-wise multiplication.

Convolutional Neural Network (CNN)

For input $x \in R^{C \times L}$:

$$\begin{aligned} z &= ReLU(Conv1D(x, W_c) + b_c) \\ p &= MaxPool(z) \\ f &= Flatten(p) \\ y &= \sigma(W_2 ReLU(W_1 f + b_1) + b_2) \end{aligned}$$

where:

- z is the resulting feature map.
- x is the input data (e.g., an EEG segment).
- Conv1D is the 1D convolution operation.
- W_c represents the convolutional filters (weights) that detect patterns.
- ReLU is the Rectified Linear Unit activation function.

Spiking Neural Network (SNN)

For a Leaky Integrate-and-Fire (LIF) neuron:

$$\begin{aligned} u_t &= \beta u_{t-1} + W x_t \\ s_t &= H(u_t - \theta) \\ u_t &= u_t \cdot (1 - s_t) \end{aligned}$$

Final output after dense layers:

$$y = \sigma(W_3 ReLU(W_2 u_T + b_2) + b_3)$$

where:

- u_t is the neuron's membrane potential at time t .
- β is the leak constant, determining how much potential is retained.
- u_{t-1} is the previous membrane potential.
- x_t is the input current.
- s_t is the output spike (1 if it fires, 0 otherwise).
- $H(\cdot)$ is the Heaviside step function, which determines the firing.
- θ is the firing threshold.

Graph Neural Network (GNN)

For a graph $G = (V, E)$ with node features $h_v^{(0)} = x_v$:

$$h_v^{(l+1)} = \sigma \left(\sum_{u \in N(v)} \frac{1}{\sqrt{d_v d_u}} W^{(l)} h_u^{(l)} \right)$$

$$H_G = \frac{1}{|V|} \sum_{v \in V} h_v^{(L)}$$

Final output:

$$y = \sigma(W_2 \text{ReLU}(W_1 H_G + b_1) + b_2)$$

where:

- $h_v^{(l+1)}$ is the updated feature vector (embedding) for node v at the next layer, $l+1$.
- $N(v)$ is the set of neighboring nodes to node v .
- $h_u^{(l)}$ is the feature vector of a neighbor node u at the current layer, l .
- $W^{(l)}$ is the shared weight matrix for layer l .
- $d_v d_u$ are the degrees of nodes v and u , used for normalization.
- H_G is the graph-level embedding

Transformer

For input sequence $X \in R^{T \times d}$:

$$Q = XW_Q, K = XW_K, V = XW_V$$

$$\text{Attention}(Q, K, V) = \text{softmax} \left(\frac{QK^T}{\sqrt{d_k}} \right) V$$

$$H^{(l+1)} = \text{FFN}(\text{Attention}(Q, K, V))$$

$$y = \sigma(W_2 \text{ReLU}(W_1 H_{[CLS]}^{(L)} + b_1) + b_2)$$

where:

- Q , K , and V are the Query, Key, and Value matrices, which are projections of the input data.

- $\frac{QK^\top}{\sqrt{d_k}}$ calculates the attention scores, indicating how much each element should focus on other elements.
- FFN is a feed-forward network
- d_k is the dimension of the Key vectors, used for scaling.
- softmax converts the scores into probabilities (weights).
- $H_{[CLS]}^{(L)}$ is the embedding of the first token after L transformer layers

Dataset

The CHB-MIT EEG database is a collection of electroencephalographic (EEG) recordings from pediatric patients with intractable epilepsy, collected at Boston Children’s Hospital, which is widely utilized in seizure research. It comprises data from 22 subjects of various ages and sexes (males and females aged 1.5-22 years), withdrawn from medication and recorded for up to multiple days. The EEG signals were recorded using the International 10-20 system, with most of them using 23 channels, sampled at 256 Hz with 16-bit resolution. In this study, data from 7 of the first patients were selected, containing a total of 32 seizure instances and approximately 442 hours of EEG recordings (23 hours after preprocessing). This selection captures a diverse range of patient profiles to evaluate each model’s ability to generalize. Data from the CHB-MIT dataset is complex and has rich temporal resolution, making it suitable for benchmarking deep learning architectures in their performance in seizure prediction.



Figure 1. EEG waveforms.

Preprocessing

The features are taken from Singh and Malhotra’s paper. The preprocessing pipeline processes raw EEG data from each of the channels, extracting 30-second segments, which are a sequence consisting of ten 3-second windows for classification into preictal and interictal classes. It takes a period of 30 minutes before a seizure as the preictal period, and excludes segments 2 hours before and after seizures for the interictal period to avoid contamination. It applies a Butterworth bandpass filter (0.1- 127Hz) to remove noise, then extracts the spectral power and

mean spectrum amplitude of five frequency bands (delta, theta, alpha, beta, gamma) using Fast Fourier Transform (FFT). Segments are then randomly shuffled and split into training (80%) and test (20%) sets. Features are then normalized before being fed into the models.

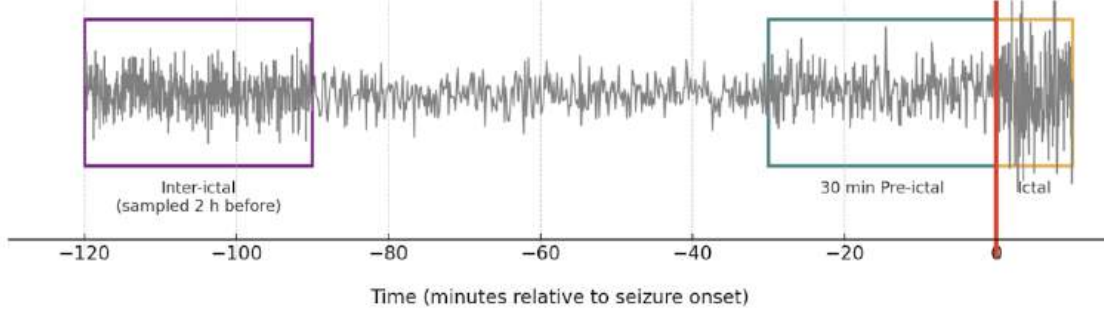


Figure 2. Different epilepsy states, along with windows used for data extraction.

Experimental setup

All models were trained using an identical preprocessing pipeline to isolate the effect of model architecture on performance. Preprocessed data is balanced to have a 1:1 ratio between the 2 labels (interictal and preictal) to have the model avoid bias and learn meaningful patterns from the data, instead of relying on learning the distribution. These methods ensure a fair and controlled benchmark and comparison of the architectures. Data is augmented using random noise addition, scaling, and temporal shifting to help the models generalize. The models are trained via backpropagation using the RMSprop optimizer with L2 regularization to further prevent overfitting. Parameters are updated based on the binary cross-entropy loss given by:

$$L_{avg} = -\frac{1}{N} \sum_{i=1}^N \left(y_i \log(\hat{y}_i) + (1 - y_i) \log(1 - \hat{y}_i) \right)$$

where:

- L_{avg} is the average loss across all samples in a batch.
- N is the number of samples in the batch.
- y_i is the true label (0 for interictal or 1 for preictal) for sample i .
- $\hat{y}_i$ is the model's predicted probability that sample i belongs to the positive class (preictal).

A learning rate scheduler is utilized to adjust the learning rate based on validation loss. The 5 models are trained on the preprocessed data with these shared hyperparameters:

Hyperparameter	Value
Batch size	32
Epochs	50
Learning rate	0.001
Optimizer	RMSprop
Loss function	Binary cross-entropy
Learning rate scheduler	Reduce-on-plateau
Weight decay	0.0001

To ensure fairness, hyperparameters were tuned using a grid search strategy that minimizes validation loss. This allows each architecture to be optimized within its own structural design. Architecture-specific hyperparameters:

- **LSTM:** hidden size {64, 128, 256}, number of layers {1, 2}, dropout {0.2, 0.4, 0.5}, dense size {64, 128}
- **CNN:** number of filters {32, 64, 128}, kernel size {3, 5}, dense size {64, 128, 256}, dropout {0.2, 0.4, 0.5}
- **SNN:** hidden size {64, 128, 256}, dropout {0.2, 0.4, 0.5}, leak constant β {0.85, 0.9, 0.95}, firing threshold $\theta = 1.0$, dense size {64, 128}
- **GNN:** hidden size {64, 128, 256}, number of layers {2, 3}, dropout {0.2, 0.4, 0.5}, dense size {64, 128}
- **Transformer:** number of heads {1, 2, 4}, feedforward size {128, 256, 512}, number of layers {2, 3}, dropout {0.2, 0.4, 0.5}, dense size {64, 128}

Each model is then evaluated by their accuracy, sensitivity, specificity, and ROC AUC metrics for each patient using a fixed test set, averaged across 10 trials to produce robust results.

Ethical considerations

The CHB-MIT dataset used in this study comprises anonymized EEG recordings. The dataset is publicly available and was gathered with Institutional Review Board (IRB) approval. All private health information was removed to ensure anonymity for participants. As this study involves secondary analysis of anonymized, publicly available data, no additional informed consent or ethical approval was required. All procedures in the data collection process and in this study adhere to ethical guidelines for research involving human subjects.

IV. Results & discussion

Results

Performance comparison of different model architectures on chb01 dataset.

Model	Accuracy	Sensitivity	Specificity	ROC AUC
LSTM	0.909 ± 0.009	0.936 ± 0.008	0.905 ± 0.010	0.964 ± 0.005
CNN	0.888 ± 0.004	0.931 ± 0.005	0.882 ± 0.004	0.934 ± 0.002
SNN	0.897 ± 0.012	0.940 ± 0.021	0.890 ± 0.015	0.958 ± 0.008
GNN	0.924 ± 0.010	0.923 ± 0.008	0.924 ± 0.013	0.959 ± 0.006
Transformer	0.893 ± 0.011	0.919 ± 0.014	0.889 ± 0.012	0.959 ± 0.003

Performance comparison of different model architectures on chb02 dataset.

Model	Accuracy	Sensitivity	Specificity	ROC AUC
LSTM	0.902 ± 0.013	0.850 ± 0.020	0.905 ± 0.015	0.937 ± 0.005
CNN	0.896 ± 0.006	0.852 ± 0.022	0.899 ± 0.007	0.930 ± 0.007
SNN	0.915 ± 0.010	0.881 ± 0.000	0.917 ± 0.011	0.950 ± 0.005
GNN	0.917 ± 0.010	0.869 ± 0.023	0.920 ± 0.011	0.952 ± 0.003
Transformer	0.905 ± 0.026	0.864 ± 0.032	0.907 ± 0.029	0.935 ± 0.008

Performance comparison of different model architectures on chb03 dataset.

Model	Accuracy	Sensitivity	Specificity	ROC AUC
LSTM	0.832 ± 0.020	0.841 ± 0.043	0.831 ± 0.025	0.927 ± 0.008
CNN	0.805 ± 0.010	0.806 ± 0.012	0.805 ± 0.011	0.899 ± 0.004
SNN	0.826 ± 0.017	0.851 ± 0.025	0.823 ± 0.019	0.927 ± 0.008
GNN	0.894 ± 0.018	0.930 ± 0.023	0.890 ± 0.020	0.972 ± 0.004
Transformer	0.867 ± 0.020	0.867 ± 0.025	0.867 ± 0.024	0.938 ± 0.005

Performance comparison of different model architectures on chb04 dataset.

Model	Accuracy	Sensitivity	Specificity	ROC AUC
LSTM	0.731 ± 0.038	0.844 ± 0.056	0.729 ± 0.039	0.844 ± 0.022
CNN	0.708 ± 0.039	0.762 ± 0.026	0.707 ± 0.040	0.780 ± 0.006
SNN	0.769 ± 0.046	0.888 ± 0.023	0.768 ± 0.046	0.900 ± 0.008
GNN	0.808 ± 0.023	0.906 ± 0.039	0.806 ± 0.024	0.904 ± 0.005
Transformer	0.666 ± 0.052	0.838 ± 0.074	0.663 ± 0.053	0.828 ± 0.054

Performance comparison of different model architectures on chb05 dataset.

Model	Accuracy	Sensitivity	Specificity	ROC AUC
LSTM	0.613 ± 0.016	0.894 ± 0.022	0.575 ± 0.018	0.814 ± 0.010
CNN	0.644 ± 0.013	0.891 ± 0.020	0.611 ± 0.016	0.826 ± 0.011
SNN	0.753 ± 0.037	0.857 ± 0.035	0.739 ± 0.044	0.864 ± 0.011
GNN	0.659 ± 0.016	0.840 ± 0.028	0.635 ± 0.021	0.822 ± 0.008
Transformer	0.609 ± 0.038	0.927 ± 0.026	0.567 ± 0.046	0.816 ± 0.016

Performance comparison of different model architectures on chb06 dataset.

Model	Accuracy	Sensitivity	Specificity	ROC AUC
LSTM	0.650 ± 0.020	0.779 ± 0.026	0.633 ± 0.025	0.762 ± 0.015
CNN	0.677 ± 0.012	0.694 ± 0.034	0.675 ± 0.017	0.755 ± 0.008
SNN	0.718 ± 0.022	0.736 ± 0.063	0.716 ± 0.032	0.806 ± 0.013
GNN	0.628 ± 0.025	0.783 ± 0.055	0.608 ± 0.035	0.759 ± 0.015
Transformer	0.602 ± 0.054	0.780 ± 0.076	0.579 ± 0.069	0.746 ± 0.015

Performance comparison of different model architectures on chb07 dataset.

Model	Accuracy	Sensitivity	Specificity	ROC AUC
LSTM	0.808 ± 0.058	0.814 ± 0.075	0.808 ± 0.061	0.905 ± 0.017
CNN	0.829 ± 0.020	0.819 ± 0.038	0.829 ± 0.021	0.925 ± 0.005
SNN	0.840 ± 0.019	0.832 ± 0.044	0.840 ± 0.020	0.918 ± 0.005
GNN	0.838 ± 0.044	0.851 ± 0.046	0.838 ± 0.046	0.933 ± 0.009
Transformer	0.849 ± 0.040	0.805 ± 0.089	0.850 ± 0.043	0.929 ± 0.015

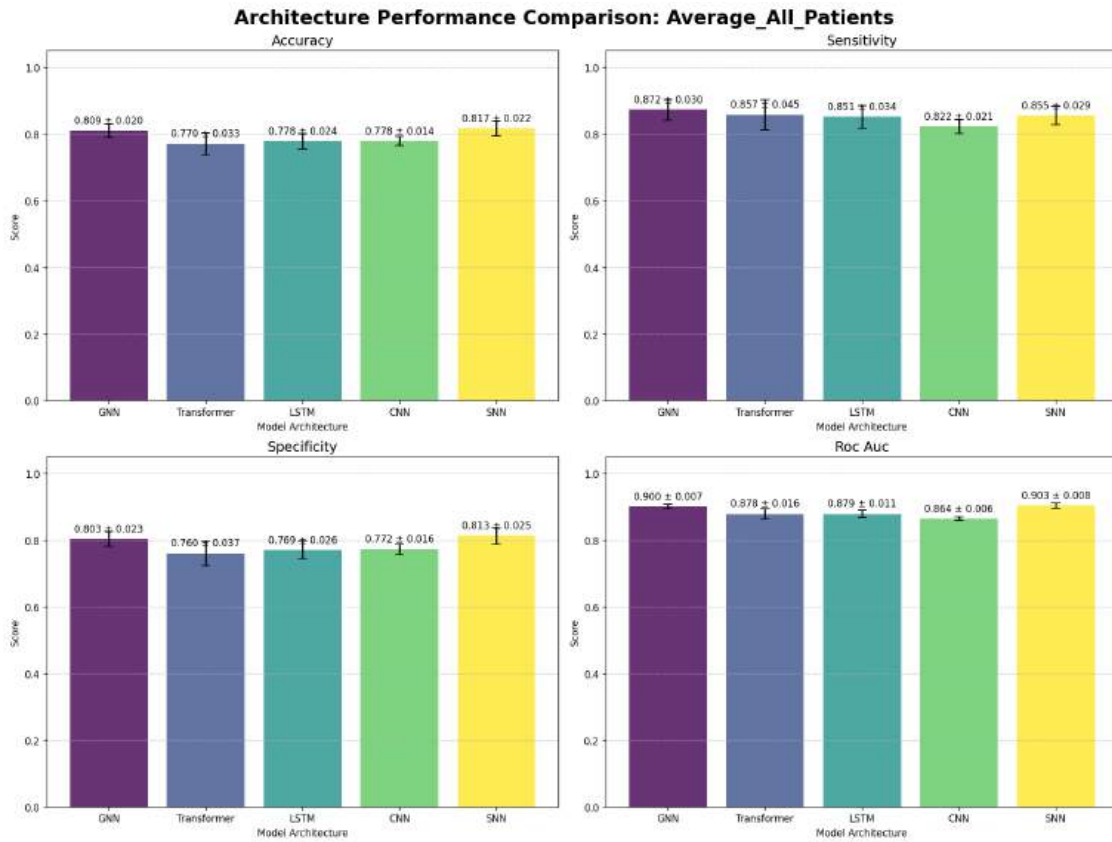


Figure 3. Average performance metrics across all patients.

Statistical Significance Analysis

To determine whether the performance differences between model architectures were statistically significant, we used a non-parametric Friedman test applied across patients for each evaluation metric. When the Friedman test indicated significant differences, we conducted post-hoc pairwise Wilcoxon signed-rank tests comparing the spiking neural network (SNN)

against each of the other models. Holm–Bonferroni correction was applied to control for multiple comparisons.

Accuracy

The Friedman test indicated significant differences across models. Pairwise tests showed that SNNs achieved significantly higher accuracy than LSTMs, CNNs, and Transformers, but not GNNs.

Sensitivity

The Friedman test indicated significant differences across models. Pairwise tests revealed that SNNs significantly outperformed CNNs but did not perform significantly better than LSTMs, GNNs, or Transformers.

Specificity

The Friedman test indicated significant differences across models. SNNs achieved significantly higher specificity than LSTMs, CNNs, and Transformers, but not GNNs.

ROC AUC

The Friedman test indicated significant differences across models. Pairwise tests indicated that SNNs achieved significantly higher ROC AUC than LSTMs, CNNs, and Transformers, but not GNNs.

Discussion

Overall, SNNs and GNNs demonstrated the best and most consistent performance, while LSTMs and CNNs generally underperformed. Specifically, SNNs achieved significantly higher accuracy, specificity, and ROC AUC than LSTMs, CNNs, and Transformers. This highlights the practical value of SNNs for seizure prediction. GNNs performed comparably to SNNs but surpassed it in sensitivity. GNNs consistently achieved the highest average sensitivity, which is critical for clinical tasks like seizure prediction. CNNs were consistently the weakest across most metrics. We also observe a high degree of performance variability across different patients. For example, most models achieved high performance metrics on the chb01 and chb02 datasets, while performance dropped substantially for chb05 and chb06. This suggests that patient-specific models or transfer learning approaches may be necessary for EEG seizure prediction.

V. Conclusion & Future Work

This study conducted a systematic evaluation of five deep learning architectures for EEG-based seizure prediction. The results show that Spiking Neural Networks (SNNs) reliably outperform CNNs, LSTMs, and Transformers across most metrics, though their performance is comparable to GNNs. This demonstrates that brain-inspired models are a promising direction for advancing seizure prediction models. However, their performance has not surpassed the best-performing conventional models. GNNs, while not significantly better than SNNs overall, achieved the highest average sensitivity, showing their potential in clinical settings. CNNs and LSTMs generally lagged behind in this benchmark. The significant patient-level variability shows

the importance of developing models that generalize across individuals or adapt to specific patients. Future work should focus on improving SNN architectures and training methods, and exploring their computational efficiency to further establish them as biologically plausible and clinically viable tools for seizure prediction.

VI. Acknowledgements

The author used publicly available data from the CHB-MIT Scalp EEG Database (<https://physionet.org/content/chbmit/1.0.0/>)

VII. Conflicts of interest

The author declares that there is no conflict of interest related to this work.

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**An Overview of the Biochemical Causes of Dementia Including Neurotransmitters
and Hormones, with Potential Treatments Discussed
By Aniketh Sadanala, Advisor By Jessica Sanchez**

Abstract

Dementia is a series of chronic, incurable neurodegenerative disorders which all commonly result in progressive psychological deterioration and eventually death. Presently, over 70 variations of dementia have been documented. This review paper covers the role of neurotransmitters (NTs) and hormones in the development/severity of the 5 most common variations of dementia: Alzheimer's Disease (AD), Lewy Body Dementia (LBD), Frontotemporal Dementia (FTD), Vascular Dementia (VD), and Parkinson's Disease (PD). NTs have proven to be crucial in maintaining neuroplasticity and basic cognitive functions. Hormones have shown their importance in long-term neurocognitive development and several biochemical regulation processes that maintain the brain's metabolism. There are several potential treatments for these variations of dementia, mainly based on NT and/or hormone level regulation therapy. A treatment strategy which combines and interchangeably utilizes NT and hormone level regulation therapy is also proposed. The goal of this review paper is to show that the main causes of dementia may be hiding in plain sight, and that with an optimistic mindset, a universal cure can be developed.

Introduction

Neurodegenerative disorders have existed for thousands of years. Dementia, in particular, is a disease that has been studied extensively for many years. Dementia constitutes impairment in memory and at least one domain of cognitive functioning (e.g. executive functioning, language, visuospatial skills, praxis, judgment, personality, abstract thinking) that represents a decrease from a previous level of functioning and results in impairment in daily activities. The variations of dementia come under two categories: Cortical and Subcortical Dementia. Cortical Dementia is usually progressive or degenerative, while tending to be associated with impaired language skills (aphasia), motor coordination (apraxia), perception (agnosia), reasoning or problem solving, learning, and recall. Subcortical Dementia may be progressive, static, or reversible and is often associated with cognitive slowing, emotionality (e.g. apathy, irritability, depression), and deficits in attention, arousal, and processing speed. Types of Cortical Dementia include: Alzheimer's Disease, Lewy Body Dementia, and Frontotemporal Dementia. Types of Subcortical Dementia include: Vascular Dementia and Dementia due to Parkinson's Disease. Below is a brief overview of each of the main variations of dementia in terms of statistics and key characteristics (Buffington et al, 2013).

Of the several different variations of dementia, the most common is Alzheimer's Disease (AD), as it accounts for roughly 50% of all cases. AD affects 11% of people aged 65 years or older and 32% of people aged 85 years or older in the United States. In 1907, Alois Alzheimer described the symptoms of his patient, a 51 year-old woman named Auguste Dieter, at the state asylum in Frankfurt, Germany: "Her memory is seriously impaired. If objects are shown to her,

she names them correctly, but almost immediately afterwards she has forgotten everything.” Alzheimer used silver staining histological technique to microscopically examine Dieter’s brain after her death. During this examination, he observed the hallmark signs of AD: Neuritic plaques (abnormal clusters of protein fragments), Neurofibrillary tangles (abnormal, insoluble twisted fibers found inside neurons), and Amyloid angiopathy (abnormal buildup of amyloid proteins in the walls of blood vessels) (Buffington et al, 2013).

Lewy Body Dementia is the second most common form of cortical dementia, accounting for 20% of all dementia cases. It is estimated that prevalence rates could be as high as 5% among the entire US population and 31% among all patients with dementia. Onset of the disease typically occurs when patients are between ages 50 and 60 years and is slightly more common in men. Major signs include a cognitive profile marked by prominent impairment in attention, visuospatial functioning, and executive functioning, as well as sleep disturbance, extrapyramidal symptoms, visual hallucinations, and fluctuations in attention and alertness. However, as stated by Lewy Body Dementia Canada: “The exact progression of a person with Lewy Body Dementia will be unique. Let go of your expectations and preconceptions, pay attention to the reality of the changes, being as flexible as possible” (Buffington et al, 2013).

Frontotemporal Dementia (FTD) is the third most common of the cortical dementias. FTD is a group of heterogeneous disorders characterized by frontal cortical atrophy, temporal cortical atrophy, or both. Family histories of FTD are seen in 20% to 40% of patients with the disease. Onset of the disease can occur between ages 35 and 75 years but most commonly occurs between ages 50 and 60 years. The most striking feature which often brings patients to clinical attention is personality change. Czech-German psychiatrist Arnold Pick is credited with several important descriptions of dementia, including the first description of FTD. He states: “The clinical findings of senile dementia can be interpreted as a mosaic of circumscribed deficits of higher mental abilities (‘Herderscheinungen’); this fact may fail to be revealed when the process of atrophy occurs simultaneously at many places, thereby masking the appearance of the single symptoms” (Buffington et al, 2013).

Vascular dementia is the second most common type of dementia, as it accounts for 10% to 50% of all cases of dementia. The disease has a prevalence rate of nearly 3% among US adults aged 65 years or older. The term *vascular dementia* is most often thought to refer to cognitive impairment associated with large-vessel ischemic cerebrovascular disease (ie, stroke). However, cognitive impairment associated with ischemic white matter lesions in small vessels is far more common. This impairment can range in severity and type depending on the location and degree of tissue damage. Alois Alzheimer also made significant contributions to the foundational descriptions of vascular dementia, initially referring to the disease as “Arteriosclerotic atrophy of the brain” (Buffington et al, 2013).

Individuals who have Parkinson’s Disease can develop slowly progressing dementia, typically later in the disease process (on average 10 years from the onset of Parkinson’s Disease). The overall prevalence of dementia in patients with Parkinson disease is approximately 30%. This prevalence increases to 48% after 15 years from initial diagnosis. For this disease, the incidence

of dementia increases with greater physical impairment. The cognitive profile is notable for predominant executive dysfunction, as well as impairments in attention, visuospatial functioning, and memory. PD was named after English surgeon James Parkinson who described the progression of the disease by stating: “As the disease proceeds, the hand fails to answer with exactness to the dictates of the will.” Now that we have discussed what each variation of dementia entails, let us move on to a series of substances with very important roles in these diseases (Buffington et al, 2013).

A key factor within the biochemical roots of AD and other neurodegenerative diseases would be neurotransmitters. Neurotransmitters (NTs) can be defined as: molecules that amplify, transmit, and convert signals in cells, having an essential role in information transmission throughout the nervous system. NTs are crucial for communicating sensory, motor, and integrative neuronal messages, affecting many functions, such as emotions, thoughts, memories, movements, and sleep patterns. Over 200 NTs have been identified since 1921, but the exact number of NTs is unknown. Canonical NTs are commonly divided into amino acids, amines, and other molecules. Amino acids represent a very important class of chemical messengers, having significant roles in the CNS.(e.g. GABA). Monoamines are a representative group of NTs with clinical significance in motor functions, emotional responses, motivations, and behavioral functions(e.g. Dopamine). Some other examples of NTs are: Acetylcholine, Adenosine Triphosphate (ATP), and Carbon Monoxide (CO). NTs are directly involved in dementia mainly through their roles in neuroplasticity and basic cognitive functions (Teleanu et al, 2022).

Another important biochemical root of AD and other neurodegenerative disorders would be hormones. Hormones can be defined as: biological compounds used by multicellular organisms to organize, coordinate, and control the functions of their cells and tissues. However, it is difficult to delineate between hormones and other factors that carry information in an organism, whether cytokines, growth factors, or autacoid factors. All three of these factors have typical hormone-like function, making them increasingly difficult to differentiate. No clear boundaries exist between hormones and other types of signaling molecules. This is because some cytokines, growth factors and autacoid factors act like typical hormones in certain situations. Some examples are: erythropoietin, fibroblast growth factor FGF23, asprosin and lipocalin-2. The role of hormones in physical and neurological growth/development and behavioral regulation makes them essential in the analysis of the biochemical causes of dementia (Stárka, Dušková, 2020).

It is important to mention that these diseases unfortunately do not currently have a cure and symptoms can only be mitigated. The treatment methods for these diseases utilize the vital roles of several neurotransmitters and hormones and their connection to dementia. Specifically, they are used to lessen the severity of and possibly begin the reversal of major symptoms across all variations of dementia. This review paper aims to exhibit the crucial role of neurotransmitters and hormones in causing neurodegenerative diseases, specifically the many variations of dementia, while also showcasing potential treatment methods that could bring humanity closer to a cure. The primary goal of this paper is to provide a potential answer to the question: “Do the

causes of dementia expand beyond hereditary contraction, and if so, can they eventually be treated?”

Key Words Dementia, Alzheimer’s Disease, Lewy Body Dementia, Frontotemporal Dementia, Vascular Dementia, Parkinson’s Disease, Neurotransmitter, Neuroreceptor, Hormone.

Methods

The NIH database Pubmed was used to acquire the studies included in this review. The terms used to search for these studies include: “Neurotransmitters and dementia”, “Hormones and dementia, and “Variations of dementia.” The studies included were all published within the last 20 years, making them fairly recent. These 12 studies thoroughly cover the roles of neurotransmitters/receptors and hormones in several variations of dementia. Demographics for these studies mostly consist of elderly patients with dementia and control groups of healthy elderly people.

Results

Alzheimer's Disease (AD)

NTs/Receptors and AD

Glutamate is one of the most abundant neurotransmitters (NTs) in the mammalian Central Nervous System (CNS). Glutamate is measured at concentrations of 5–15 μ mol/g in wet tissue. The vast majority of the excitatory neurotransmission in the mammalian CNS is mediated by glutamate and its receptors, mainly iGluRs, ligand-gated ionotropic (a group of transmembrane ion-channel proteins which open to allow ions to pass through the membrane) glutamate receptors. iGluRs also play fundamental roles in synaptic plasticity, the underlying molecular mechanism behind learning and memory. The disruption of the normal signaling via iGluRs is implicated in a wide range of neuropathological disorders and diseases such as epilepsy and brain damage, Parkinson’s Disease (PD), AD, Huntington’s, Multiple Sclerosis (MS), thereby making iGluRs important drug targets for therapeutic purposes. One particular subgroup of iGluRs is selectively gated by specific agonists N-methyl-d-aspartate (NMDA), thus named as NMDA receptor (NMDAR) (Figure 1.). Insufficient synaptic NMDAR signaling greatly compromises neuronal cell survival (Wang, Reddy, 2018).

However, excessive stimulation of glutamatergic signaling results in excitotoxicity, the pathological process where nerve cells are damaged and killed or neurological trauma such as stroke occurs due to excessive stimulation from neurotransmitters, primarily glutamate. Many studies indicate a role for glutamate excitotoxicity in delayed slowly-evolving neurodegeneration. The glutamate uptake and recycling system is an important factor that determines the availability of glutamate for signaling processes. This system can be severely weakened in AD. Furthermore, EAAT 2, excitatory amino acid transporter 2, which is critical in glutamate removal, that is

primarily located in perisynaptic astrocytes (Fine leaflets that are critical for modulating synaptic function), was reported to have impaired function in AD. Studies using several species of A β peptides (The main component of the amyloid plaques found in the brains of people with Alzheimer's disease) in neuronal cell culture also support the idea that toxic A β may allow more glutamate availability by impairing glutamate uptake/recycling mechanisms. This overflowing glutamate supply is likely to contribute to AD-associated excitotoxicity and neurodegeneration (Wang, Reddy, 2018).

The integrity of the presynaptic neurotransmitter release machinery also contributes to the availability of glutamate. A β can significantly reduce the expression of presynaptic proteins such as synaptophysin, syntaxin, and synaptotagmin, many of which are active components of the neurotransmitter release machinery. AD may also enhance NMDAR signaling through the modulation of the receptor itself. Various studies have demonstrated that A β directly modulates the electrophysiological function of NMDARs. A β could possibly even physically interact with NMDARs, either directly or via synaptic proteins such as PSD95 which participate in important signaling pathways within synapses. AD also affects the level of NMDAR coagonists which bind with and activate a response from NMDARs. Complete activation of NMDARs by glutamate requires the continuous binding of coagonist D-serine or glycine, and therefore these coagonists play an important modulatory role in NMDAR function. The role of NTs/receptors in the processes discussed in this section illustrates their significance in AD pathogenesis (Wang, Reddy, 2018).

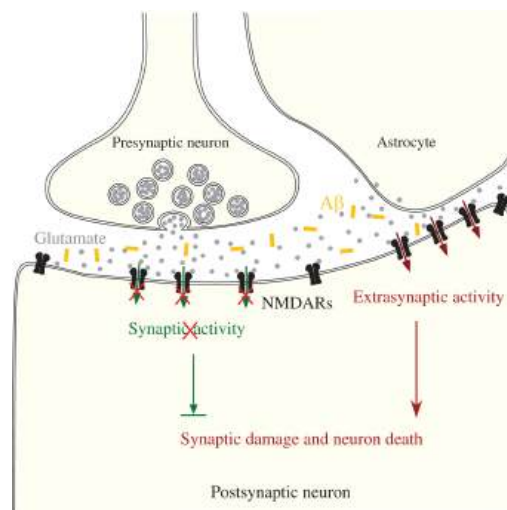


Figure 1: Model of NMDAR dysfunction causing synaptic damage or neuronal death which marks the development of AD (Wang, Reddy, 2018).

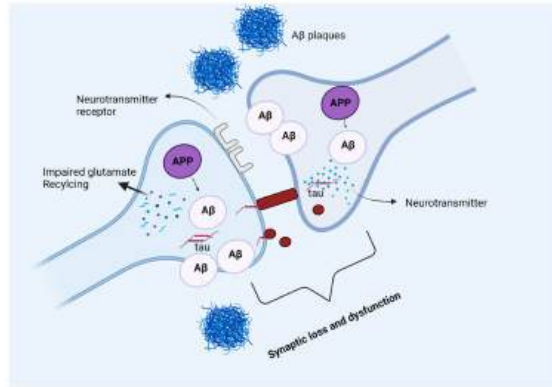


Figure 2: Model of AD hallmark A β plaques impairing glutamate recycling, causing synaptic loss and dysfunction (Sehar et al, 2022).

Hormones and AD

Leptin is a pro-inflammatory adipokine, which is a Signaling molecule that promotes inflammation and is secreted by White Adipose Tissue (WAT) and found to be increased in people with a high body mass index. This hormone acts centrally at the level of the hypothalamic region through anorexigenic (suppresses appetite) proopiomelanocortin (POMC)/cocaine- and amphetamine-regulated transcript (CART) neurons and orexigenic (stimulates appetite) neuropeptide Y (NPY)/agouti-related peptide (AgRP) neurons. These neurons play a major role in controlling food intake and energy expenditure. It is suggested that leptin may be the link between obesity and dementia through the development of inflammation. Leptin signalling regulates different processes such as: food intake, energy expenditure, cognition, learning, memory, and mood. In addition, leptin regulates neurogenesis (neuron formation), synaptogenesis (synapse formation), neuronal excitability, and neuroprotection. The mechanisms of long-term potentiation (LTP) and long-term depression (LTD) of synaptic transmission are crucial for the formation and consolidation of hippocampal memory. Leptin is involved in these processes at the level of the hippocampus where leptin and glutamate receptors {N-methyl D-aspartate (NMDA) and α -amino-3-hydroxy-5-methyl-4-isoxazolepropionic acid (AMPA) receptors} are key players. Leptin also regulates the configuration, or physical structure, of neurons. As a result, plasma leptin levels (leptin concentration in the bloodstream) have been associated with grey matter volume in various brain regions. Grey matter is crucial for information processing and various cognitive functions. Studies show leptin is secreted by adipocytes (fat cells) and circulates in plasma in proportion to fat mass, and changes in body weight are associated with the possibility of developing AD. These studies suggest that plasma leptin deficiency could indicate a possible CNS leptin deficiency and thus serve as a diagnostic marker for MCI or AD. This information reveals leptin's significant role in diagnosing and analyzing AD (Flores-Cordero et al, 2022).

Another important hormone associated with AD is Melatonin. Melatonin (N-acetyl-5-methoxytryptamine), is a tryptophan metabolite (metabolized from tryptophan) and synthesized mainly in the pineal gland. This hormone has a number of physiological functions,

including regulating circadian rhythms, clearing free radicals (highly unstable molecules), improving immunity and generally inhibiting the oxidation of biomolecules (electron loss that leads to damaged biomolecule functioning). Decreased melatonin in serum (The fluid component of blood) and cerebrospinal fluid (CSF) and the loss of melatonin diurnal rhythm (melatonin level regulation based on time of day) has been observed in AD patients. In addition, the level of melatonin in CSF decreases with the progression of AD neuropathology. Melatonin levels in both CSF and postmortem human pineal gland are already reduced in preclinical AD subjects, who are cognitively intact at the time and have only the earliest signs of AD neuropathology. There is a strong correlation that exists between pineal content and CSF level of melatonin and between CSF and plasma melatonin levels, which suggests that a reduced CSF melatonin level may serve as an early marker for the very first stages of AD. Since increasing melatonin levels improves some of the clinical symptoms of AD, and since the level of melatonin decreases dramatically during AD, studies on the relationship between melatonin and AD pathology will be helpful to assess its potential in the prevention or treatment of AD. These studies show that leptin and melatonin are major risk factors for the development of AD through neurodegeneration.

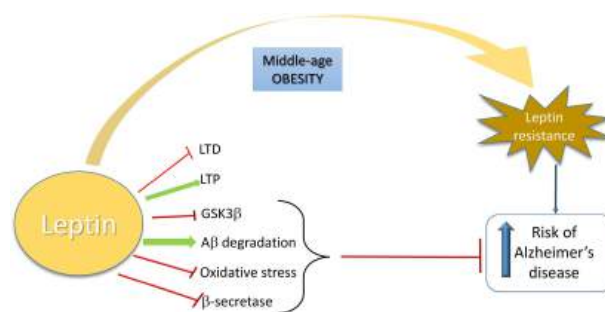


Figure 3: Model of the role of leptin resistance in increasing the risk of contracting AD (Lloret et al, 2019).

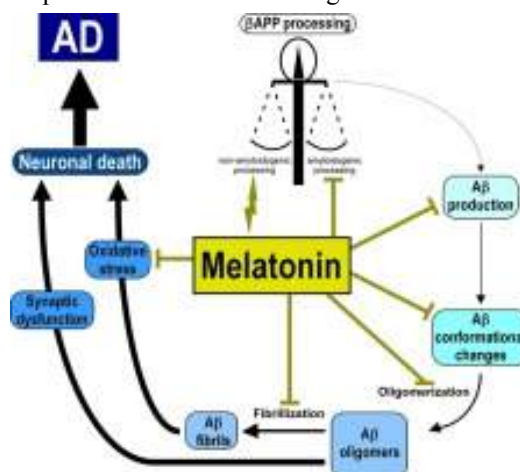


Figure 4: Model of the role melatonin in causing neuronal death, which in turn leads to AD (Vincent, 2018).

Lewy Body Dementia

NTs/Receptors and LBD

Dementia with Lewy Bodies (DLB) is characterized by cholinergic (relating to the NT system of Acetylcholine (ACh) deficits. Cholinergic input from the Nucleus Basalis of Meynert (NBM), a key structure in the basal forebrain, is required for cognitive functions (including memory), and degeneration of the NBM in DLB contributes to the decline in cognitive function observed in patients with this disease. Analysis of cholinergic activity in the brains of DLB patients showed that deficits are greater in some regions of the temporal cortex of those with visual hallucinations vs those without visual hallucinations. Visual hallucinations are a hallmark symptom of DLB. There are abnormalities in ACh receptors in DLB patients, specifically muscarinic receptors. The neurochemistry of muscarinic receptors is complex because different muscarinic receptor types control the stimulation and inhibition of ACh released by the presynaptic cell. In addition, the presence of more than one type of muscarinic receptor on the postsynaptic cell can result in a complex response in the postsynaptic neuron to ACh release by the presynaptic cell. The prevalence of the cholinergic system is further exhibited by other receptors that act as components of the system (Perry, Perry, 1993).

Another important component of the cholinergic system is the presence of nicotinic receptors. Nicotine receptor stimulation on the presynaptic cell results in the release of ACh and other neurotransmitters involved in cognition and behavior. Nicotine receptors are composed of five protein subunits in combinations of α - or β -type subunits (heteromeric) or only one type of subunit (e.g. all α). Different subunit combinations display different ligand-binding characteristics and functional activity, and it is presumed that different combinations of subunits have different functions depending on where they are expressed. These subunits overall play a crucial role in neural and neuromuscular transmission by forming ion channels that allow for rapid communication between nerve cells. Patients suffering from DLB are shown to have significant nicotinic receptor loss, particularly in the dentate granular area, which functions in learning, memory, and spatial navigation. This may have an effect on memory loss in DLB patients. Muscarinic and Nicotinic receptors are two important factors in the cholinergic system, and the undeniable prevalence of the cholinergic system in basic cognitive/bodily functions directly links these receptors to DLB pathogenesis (Perry, Perry, 1993).

A β Peptides and LBD

A β peptides play a significant role in the pathogenesis of DLB. It is suggested that by interacting with the neuronal protein α -synuclein, the amyloid peptides promote aggregation (clumping of proteins into abnormal structures), enhance the accumulation of α -synuclein pathologies, and accelerate cognitive dysfunction. The altered brain processing of Amyloid Precursor Protein (APP), which leads to accumulation of extracellular amyloid deposits throughout the brain tissue of the affected individuals, is also seen in the periphery, for example, CSF and blood derivatives (therapeutic substances derived from human blood/plasma). Hence,

the CSF decrease of A β peptide 1-42, although characteristic of AD, is also found in DLB. According to one study, the shorter amyloid peptide (A β 1-40) also appears to be decreased in patients with DLB. In addition, the ratio between the longer and shorter CSF amyloid peptides (A β 42/A β 40) appears to be superior in discriminating between AD and other neurodegenerative disorders, including DLB, than the A β 42 measure alone ($P < .01$), with the former being equally robust as the combination of A β 42, p-tau181, and t-tau biomarkers. These ratios reveal the statistical significance of A β peptides in DLB. In summary, this evidence shows that A β peptides are not just directly linked to DLB pathogenesis but are also important biomarkers for the disease (Mukaetova-Ladinska et al, 2010).

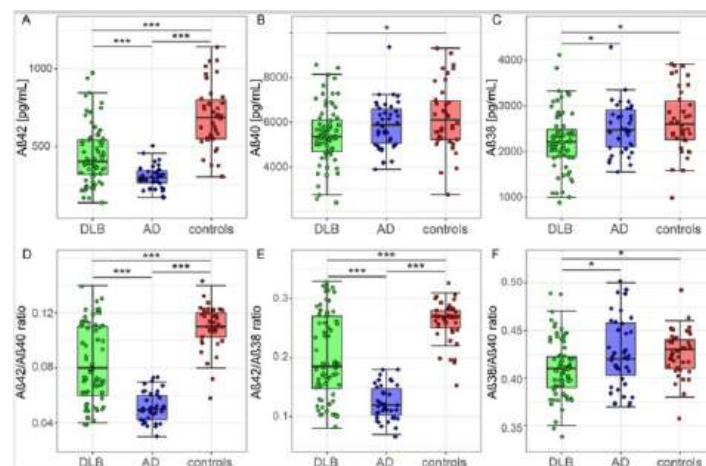


Figure 5: Study comparing CSF A β peptides in DLB, AD, and controls. Each graph compares the levels of different A β peptides in DLB, AD, and healthy control groups. (Steenoven et al, 2019).

Frontotemporal Dementia

NTs/Receptors and FTD

There is both preclinical and clinical evidence that glutamate is important in the pathogenesis of FTD. An example can be seen in transgenic mice. Transgenic mice that express pathological human tau (abnormal forms of tau protein) have repetitive and disinhibited behaviour, coupled with NMDA receptor hypofunction. NMDA agonist treatment restores their behavior. Several mouse models expressing pathological human tau suggest glutamate mediated excitotoxicity may accelerate neuronal loss in tauopathies such as FTD. Magnetic resonance spectroscopy of patients suffering from FTD has found glutamate/glutamine levels are reduced in the frontal and temporal lobes. Furthermore, ionotropic (function as transmembrane ion channels) and metabotropic (indirectly trigger a chain of intracellular reactions) glutamate receptors are affected in FTD. Through usage of the ligand 11C-ABP688, PET scans of patients with FTD found reduced availability of metabotropic glutamate receptors (mGluR5) in the frontal and temporal lobes, basal ganglia and thalamus. This reduced ability disrupts the modulation of synaptic transmission and neuronal excitability, contributing to neurodegeneration. In addition,

other NTs play an equally important role as Glutamate and its receptors in FTD (Murley, Rowe, 2018).

Other important neurotransmitters related to FTD are dopamine and serotonin. The areas of the cortex degenerated in FTD receive strong dopaminergic projections. There exists clinical evidence of basal ganglia dopamine dysregulation (i.e. parkinsonism) in FTD and FTD variants such as frontotemporal dementia and parkinsonism (FTDP-17). This observation is supported by a PET study that showed decreased presynaptic dopamine transporter in the putamen (a rounded subcortical nucleus) and caudate (involved in several motor/nonmotor functions) of patients with FTD. The anatomic and clinical presentation of FTD also corresponds well to serotonergic dysfunction: There are strong serotonergic projections to the frontal cortex from the raphe nuclei (a series of nuclei in the midline of the brainstem), low brain levels of serotonin have been associated with aggression and impulsiveness, depressive symptoms, and alterations in frontal cortex metabolism. The symptoms of FTD also overlap considerably with those of psychiatric disorders treated with serotonin augmentation such as depression and obsessive-compulsive disorder. These connections through anatomy and clinical similarities prove that NTs/receptors are rather influential in the development/severity of FTD (Huey et al, 2006).

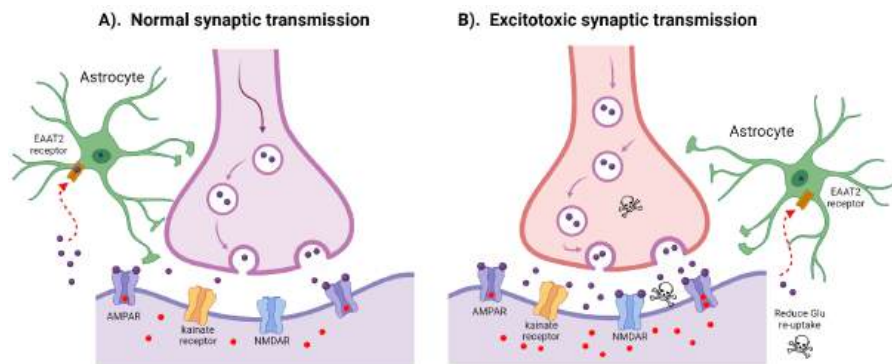


Figure 6: A model comparing normal synaptic transmission with excitotoxic synaptic transmission in FTD and other variations of dementia (Arnold et al, 2024).

Progranulin and FTD

Human Progranulin (PGRN) is an evolutionarily conserved 593–amino acid glycoprotein. PGRN has 593 amino acids in its polypeptide chain and has one or more carbohydrate (sugar) chains attached to it with an apparent molecular weight of ~88kDa. This glycoprotein can be secreted and is enriched in lysosomes (contains degradative enzymes in a membrane). This protein is ubiquitously expressed (produced in all cell types), and, in the CNS, it is highly expressed in microglia and, to a lesser extent, in neurons and other cell types. Traumatic brain injury (TBI) can actually be linked to a PGRN deficiency which increases the risk of FTD. Evidence suggests that the CNS levels of elastase (enzyme that breaks down elastin, a protein that provides elasticity to connective tissues) increase after spinal cord trauma and stroke. Increasing elastase levels are also likely after TBI as it leads to activation of microglia, which in turn secrete

multiple cytokines including elastase. This reveals the possibility that TBI may cause an increase in elastases, which would result in a reduction in the levels of PGRN and an increase in the proinflammatory GRNs. Reduced PGRN levels in turn impair lysosomal function which leads to the accumulation of cellular waste, contributing to the development of FTD. TBI is not the only cause of PGRN deficiency, however. Mutations in the GRN gene, which encodes for PGRN, can disrupt and impair PGRN function. These mutations are a major cause of FTD. In summary, PGRN is one of the most important non-NT substances involved in FTD pathogenesis due to its presence in all cell types and the CNS (Jawaid et al, 2010).

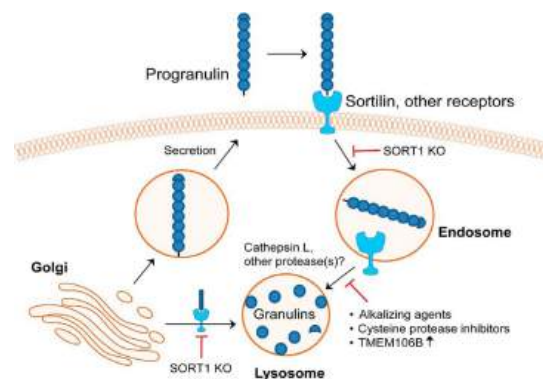


Figure 7: A model portraying the function of PGRN and its enrichment by lysosomes (Holler et al, 2017).

Vascular Dementia

Glutamate/Receptors and VaD

Glutamate, being the most abundant amino acid and the primary excitatory neurotransmitter in the central nervous system of vertebrates, is directly involved with the development of several neurodegenerative disorders including VaD. Specifically, the glutamatergic system plays a role in VaD pathogenesis. Inadequate blood supply to the brain caused by cardiovascular disease is one of the important mechanisms underlying VaD, leading to neuronal death and cognitive and behavioral impairment. Furthermore, when the brain experiences ischemia and hypoxia due to cardiovascular disease, ATP production is reduced, resulting in abnormal function of the Na^+/K^+ ATPase (NKA), $\text{Na}^+/\text{Ca}^{2+}$ exchange (NCX), and Ca^{2+} ATPase plasma pump (crucial pumps for maintaining cellular ion homeostasis) on the cell membrane. These in turn disrupt ion gradients inside and outside the cell membrane and cause cellular dysfunction, including glutamate metabolism. The metabolic dysfunction of glutamate increases glutamate release and inhibits glutamate recycling, leading to excessive intercellular glutamate accumulation and receptor activation as well as tonic cell excitability, known as "glutamate excitotoxicity." Moving on, neuronal cells, particularly those in the hippocampus, are sensitive to fluctuations in glutamate levels (Wang et al, 2024).

Several studies have suggested that insufficient cerebral blood supply in pre-VaD leads to increased glutamate release. In addition, activation of the two-pore potassium channel (potassium channels characterized by having two pore-forming regions (or "pores") in each subunit) TWIK-related K channel (TREK-1), found in many neuronal cells and astrocytes, can mediate rapid glutamate release and increase cognitive impairment due to glutamate toxicity. AMPARs, or glutamate receptors, also play a role in VaD. AMPARs are expressed in vascular smooth muscle cells and are involved in the control of blood vessels. In a mouse model of VaD, NBQX, an AMPA receptor inhibitor, was administered to the mice, and it was shown to have significantly lessened axonal degeneration. This suggests that AMPA could potentially play a role in synaptic degeneration under VaD pathology. The evidence above reveals the importance of NTs and receptors in VaD pathogenesis and also in major risk factors for VaD (Wang et al, 2024).

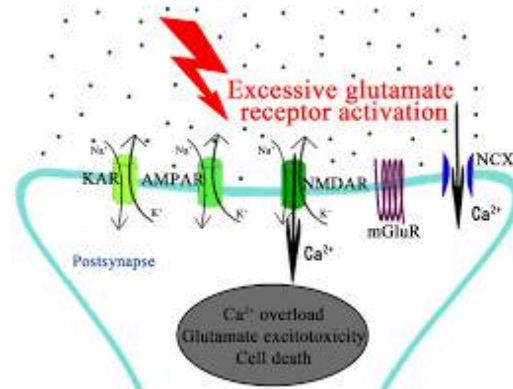


Figure 8: A model of excessive glutamate receptor activation, leading to glutamate excitotoxicity and cell death (Wang et al, 2024).

Hormones and VaD

Studies have been conducted in order to investigate the controversy between correlating estrogen changes to cognitive impairment, which causes VaD. This is due to the sudden downfall of estrogen in women during menopause; this happens to be one of the significant risk factors and the root prevalence of VaD in postmenopausal females. In addition, studies have concluded that estrogen deficiency in postmenopausal women is indeed one of the risk factors, causing cognitive deficit that can lead to VaD. One study focused on the serum sex hormone levels among VaD patients. The study's results revealed that the testosterone and sex hormone-binding globulin (SHBG) levels were lower in male VaD patients, and the estradiol levels were found to be higher in female VaD patients in comparison to the controls. The final conclusion of the study was that there were no correlations between hormone levels and neuropsychiatric symptoms in male VaD patients, whereas total estradiol (TE2) and testosterone (TT) levels were positively correlated in female VaD patients. One study suggests that estrogens and their receptors may regulate the neuroinflammatory response, and in females, circulating estrogens may play a protective, anti-inflammatory role. Hence, estrogen preserves vascular function and neuroinflammatory response, suggesting that this hormone could be directly relevant to VaD. The results of these

studies show that hormones could potentially have a significant role in VaD pathology and development (Akhter, et al).

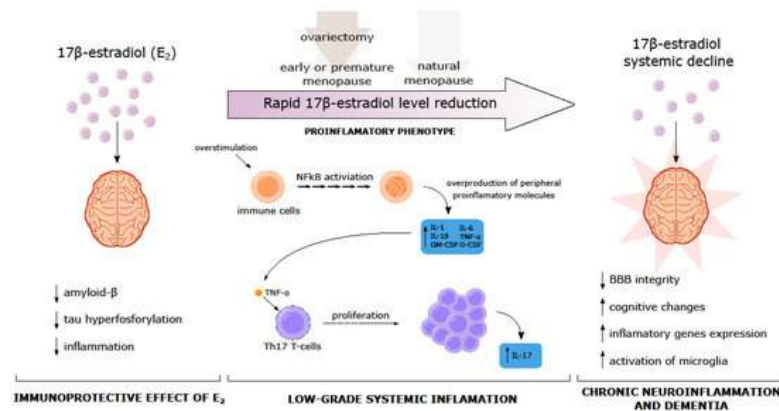


Figure 9: A model of estradiol level reduction, which in turn leads to neuroinflammation and VaD (Sochocka et al, 2023).

Parkinson's Disease (PD)

Dopamine (DA) and PD

The impairment of DA release plays a significant role in the development/pathology of PD. DA release is mediated/controlled by Ca²⁺ and Rab3-interacting molecule-dependent vesicular exocytosis (process by which cells release molecules stored in membrane-bound vesicles in response to specific molecular signals or machinery) from active zone-like sites. Released DA is thought to act beyond individual synapses at extrasynaptic receptors on many cells and can also be released from the cell body and dendrites through somatodendritic release. The DA release process is highly regulated through a variety of mechanisms, including DA synthesis, cell and vesicular uptake, action potential propagation and local neuromodulatory receptors. *In vivo*, DA release dynamics are thought to be determined by a combination of different DAN firing rates (tonic low frequency pacemaking, sustained increases in firing rate and short intermittent or 'phasic' bursts at high frequencies), as well as by a range of mechanisms operating on DA axons that can locally gate action potential propagation, DA release probability and its dynamics during activity. Several animal and human cell-based models of PD have demonstrated early synaptic dysfunction and intrinsic DA release defects. The mechanisms by which these defects occur can be categorized into six mechanisms: SV exocytosis, SV trafficking and loading, SV endocytosis and recycling, synaptic protein accumulation, damage to the SV pool and non-cell autonomous mechanisms. Most DA release is mediated by Ca²⁺-dependent vesicular exocytosis. Disruption to this process will cause impairment in DA release (Cramb et al, 2023).

In addition, normal synaptic functioning in DA axons requires the formation of the SNARE complex (group of proteins crucial for membrane fusion) by vesicular

synaptobrevin-2/VAMP-2 and syntaxin-1/SNAP-25 on the plasma membrane. PD proteins such as α -synuclein and LRRK2 directly interact with SNARE proteins and PD-related mutations either alter activity or expression of SNARE complex. Furthermore, the addition of α -synuclein oligomers (proteins that regulate the amount of SNARE complex, which regulates the release of neurotransmitters) inhibits SNARE-complex formation by binding SNARE protein synaptobrevin-2. Exocytosis also requires high energy levels in the form of mitochondrial ATP. PD mutations along with α -synuclein oligomers can impair mitochondrial function or transport leading to an axonal energy deficit and synaptic loss. Defective mitochondria may also disrupt exocytosis through calcium dysregulation, since these organelles are essential for calcium buffering. DA release can also be impaired by unavailability of DA in the readily releasable pool at presynaptic terminals, through defects in synthesis, vesicular loading or trafficking. DA loss in the SVs by disturbed synaptic loading not only leads to a lack of availability of DA for release but the consequent increase in cytoplasmic DA may have toxic effects on the cell as it is rapidly converted to a reactive species (unstable molecules that readily react with other cellular components). In addition, intracellular and specifically axonal and vesicular trafficking is impaired in PD with consequences to synaptic function. DA release deficit could also be a result of direct damage to the SV pool. This could possibly occur through generation of Reactive Oxygen Species (ROS), a common hallmark of PD (Cramb et al, 2023).

Furthermore, cytosolic DA, which is increased in PD models, undergoes auto-oxidation, creating further ROS. An increase in cytosolic DA may be caused by a number of factors, including impaired DA loading into SV or increased DAT activity, both connected to PD. ROS overproduction inhibits SNARE-complex assembly and thus impairs exocytosis. Damage to the SV pool also occurs when protofibrillar α -synuclein and oligomers disrupt the SV membrane allowing DA to spill out into the cytosol (fluid portion of the cytoplasm within a cell) and alter neuron excitability. The ability to reconstitute the vesicular pool for subsequent release events is regulated by vesicle renewal/reuptake, recycling and reloading of the neurotransmitter into SVs.

There is substantial evidence that links PD with defects in SV endocytosis and recycling. Both complete DJ-1 knockout as well as PD-related DJ-1 mutations disrupt SV endocytosis. Further evidence supports that defective SV recycling and decreased reuptake of DA leading to lack of SV replenishment could be an important contributing factor to disruption of DA release in PD. Another major hallmark of PD is protein aggregation. α -synuclein aggregation in particular may induce DA release defects by physically blocking cell processes caused by the aggregate itself or rather through sequestration of the functional protein, leading to disruption of synaptic processes by loss of protein function. Autophagy, a major protein degradation pathway, is crucial for regulation of protein turnover in neurons and has been connected to Parkinson's disease-related mutations including SNCA, LRRK2, VPS35, parkin, Pink1 and DJ-1. This particular pathway appears to be specifically important for synaptic homeostasis in DA systems. Thus, protein aggregation may disrupt DA release through sequestration of essential proteins or by physical interference in critical processes for release. These essential processes involving DA prove its importance in the development and diagnosing of PD (Cramb et al, 2023).

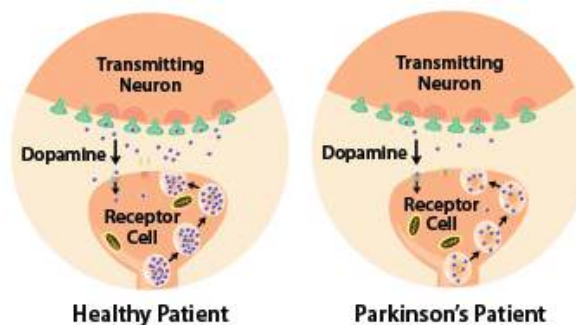


Figure 10: A model comparing the DA pathway in a healthy patient to that of a PD patient (OHSU, 2025).

Hormones and PD

Cortisol and other Glucocorticoids (GCs) also play a role in the development/pathology of PD. Glucocorticoids are essential to homeostasis and a normal response to stress. Chronic stress and elevated cortisol are implicated in many of the mechanisms that are implicated in the progression and, potentially, development of PD including metabolic changes, mitochondrial dysfunction, and neuroinflammation. Excessive cortisol secretion promotes neuroinflammation through the mechanism in which glucocorticoid receptors or GR (anti-inflammatory actions) are downregulated as a compensatory response to excess cortisol production and GC resistance, which further promote the release of GCs. Catecholamines and glucocorticoids under normal conditions regulate inflammation through the inhibition of proinflammatory cytokines, such as IL-6, IL-1 β , and TNF- α , and the stimulation of anti-inflammatory cytokines, such as IL-4, IL-10, and IL-13 [38], by exerting action in the cytoplasm of immune cells. However, through an interplay of inflammation due to immune response and subsequent cytokine release and a lack of downregulation normally executed by GCs, neuroinflammation persists, leading to the atrophy of neurons in critical brain areas, such as the hippocampus. Neuroinflammation is prominent neurodegenerative diseases including PD, and may be the driving factor in both the progression of and contribution to disease development. Thus, dysfunctional hormone level regulation may be linked to PD as such dysfunction allows neuroinflammation to persist (Knezevic et al, 2023).

Discussion

The important role of NT/receptor and hormone dysregulation in Alzheimer's Disease, Lewy-Body Dementia, Frontotemporal Dementia, Vascular Dementia, and Parkinson's Disease has been thoroughly reviewed in the results section. Most often the NTs involved have specific metabolic functions, contribute to basic cognitive functions, and/or are crucial to maintaining synaptic plasticity. The neuroreceptors are mainly involved in the functioning of specific NT systems. The hormones have several functions varying from reproductive development to maintaining homeostasis. It is important to discuss the comparison of NTs and hormones in detail due to the complex nature of their involvement in these variations of dementia.

Glutamate and Dopamine both have significant effects in dementia pathogenesis and are two of the most common NTs associated with dementia. However, the roles they play in the disease are rather different. Glutamate's main connection to dementia is the process of glutamate excitotoxicity, while dopamine's main connection is through dopamine transporter dysregulation, which in turn leads to decreased dopamine levels, finally leading to neurodegeneration and dementia. Despite these differences, glutamate receptors and dopamine protein degradation pathways function similarly. iGluRs (glutamate receptors) are extremely important in synaptic plasticity/homeostasis, the underlying molecular mechanism behind learning and memory. Autophagy, a major protein degradation pathway, is crucial for regulation of protein turnover in neurons and also appears to be specifically important for synaptic homeostasis in dopamine systems. These NTs and their roles in the brain prompt further research into the maintenance of NT systems/pathways in order to prevent NT level dysregulation. Other important processes including synaptic homeostasis are also heavily regulated/influenced by hormones. (Wang, Reddy, 2018), (Cramb et al, 2023).

Leptin and Progranulin are a major hormone and a multifaceted protein, respectively, commonly involved in dementia. Both of these substances have separate roles in the human body but have similar implications in dementia pathogenesis. Leptin, a pro-inflammatory adipokine (Signaling molecules that promote inflammation), is secreted by White Adipose Tissue (WAT) and found to be increased in people with a high body mass index. Leptin signalling regulates various crucial processes including food intake, energy expenditure, cognition, learning, memory, and mood. From a neurocognitive perspective, leptin regulates neurogenesis (neuron formation), synaptogenesis (synapse formation), neuronal excitability, and neuroprotection. In contrast, progranulin is a glycoprotein which is ubiquitously expressed (produced in all cell types), and, in the CNS, highly expressed in microglia and on a smaller scale in neurons and other cell types. On the other hand, both leptin and progranulin deficiencies serve as diagnostic biomarkers/risk factors for dementia. Leptin is secreted by adipocytes (fat cells) and circulates in plasma in proportion to fat mass, and changes in body weight are associated with the possibility of developing dementia. Thus, according to the studies cited, plasma leptin deficiency could indicate a possible CNS leptin deficiency and thus serve as a diagnostic marker for dementia. Similarly, reduced PGRN levels impair lysosomal function which leads to the accumulation of cellular waste, contributing to dementia pathogenesis. The functional stronghold that these hormones have at the cellular level prompts further investigation into the correlation between hormone levels and cell death rates. This research may open windows for the potential usage of hormone/cell regeneration therapy for the treatment of dementia (Flores-Cordero et al, 2022).

Based on the significant information collected from the several studies reviewed in the results section, it is recommended that scientists focusing on this topic delve deeper into the implications of neurological processes involving neurotransmitters/receptors and hormones as risk factors and/or important biomarkers for the several variations of dementia. Understanding these implications may lead to breakthroughs in the research of more well-known, less

foundational causes of dementia such as genetic/hereditary causes and risk factors. Fortunately, there are several treatments to mitigate the symptoms/development of dementia.

This section primarily reviews treatments from the studies cited in the results section. One of the most actively explored treatment strategies is the enhancement of cholinergic activity. Cholinergic compounds currently being tested are clinically composed of first generation drugs and second generation drugs. For example, refined cholinesterase inhibitors (whose structural and biological diversity is enormous) with anatomical selectivity, fewer side effects and broader therapeutic ratios are currently being enlisted in new clinical trials. One major byproduct of efforts in designing cholinergic cognitive therapy is the potential application to the so-called mild memory impairment which can occur in normal individuals over the age of 50. There is also scope for applying drugs developed for dementia as cognitive enhancers for younger individuals who feel the need to improve memory performance: The so-called 'smart' drugs. Another potential treatment strategy is hormone replacement therapy (HRT). In a recent study, AD and related dementias were reported less frequently on death certificates among subjects undergoing estrogen replacement therapy (ERT) than among nonusers (relative risk = 0.69, 95% confidence interval = 0.46 to 1.00). The risk levels for dementia and AD decreased with increasing doses of estrogen and with increasing intervals of use. Another observational study demonstrated that estrogen use may delay the onset of AD. Participants in the study included 1124 postmenopausal women who were initially free of cognitive impairment and who had follow-up 1 to 5 years after baseline. AD developed in 5.8% of the women taking estrogen after menopause in comparison with 16.3% of the nonestrogen users ($P = 0.001$). Again, the risk for Alzheimer's disease decreased with longer duration of estrogen use. Participants using estrogen for 1 year or less showed lower risk for Alzheimer's disease; however, women taking estrogen for over 1 year had the greatest reduction in risk.

Based on the information reviewed in this paper, another potential treatment would be a combination of neurotransmitter level alteration and hormone therapy. Both treatment regimens can either be administered simultaneously or one after the other. The treatment that proves more effective will be continued until the patient either begins showing signs of recovery or until the progression of dementia is significantly decreased. If signs of recovery begin to show, the strength of the treatment will be increased. However, if the progression is simply mitigated, the treatment can either be continued at a similar strength or stopped completely, depending on what the patient/patient's loved ones prefer at that time. An example of a pharmaceutical therapy combination is the combination of Estrogen Replacement Therapy(ERT) and dual-action antidepressants to increase dopamine levels in female PD and VaD patients. An example of a combination of non-pharmaceutical therapies is the administration of Cognitive Behavioral Therapy(CBT) and stress management routines to decrease cortisol/glucocorticoid(GC) levels which hold visible significance in PD pathogenesis.

Ultimately, although dementia is currently a class of several incurable and incredibly varying neurodegenerative syndromes, many of these variations have relations through grassroots causes/risk factors in the form of neurotransmitters/receptors and hormones. This review should

be taken into direct consideration during further dementia research because it provides a thorough description of the neurobiological processes that neurotransmitters/receptors and hormones are involved in and how they relate to the development/severity of dementia and supports this description with numerous studies from reputable sources. This review may encourage forward progression towards making a breakthrough in potentially universal cures or treatment plans for the condition as a whole. The next step is to apply this research in more advanced, trial-and-error based scientific studies while also making this key information readily available/understandable to the general public.

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Conversion Disorder: Causes and Connections By Sarah Li

Abstract

Conversion disorder symptoms are seen in up to 20 to 25 percent of hospital patients. However, even though many patients are diagnosed with conversion disorder, not much research has been developed to treat this condition. Conversion disorder is identified by physical symptoms with no biological explanation and is usually caused by psychological stress. Here, we compiled the known research on potential causes of conversion disorder. We highlight the potential genetic, stress response, and microbiome derived causes of conversion disorder. Overall, we provide evidence for a mutation in tryptophan hydroxylase, exposure to traumatic events and stress, and microbiome dysbiosis as leading candidates for the onset of this disorder. Based on this evaluation, we propose potential treatment options to aid with conversion disorder symptoms. This includes adding fermented foods, Omega-3, or prebiotic foods to mainstream treatments. Taken together, using the information compiled in this review, and considering the suggested novel treatment supplements, new progress can be made in the fight against this disorder.

Introduction

Conversion disorder, also called functional neurological disorder, is defined as a condition where individuals experiencing psychological stress manifest physical symptoms that can not be explained through medical diagnoses. (“Conversion Disorder”) 20 to 25 percent of hospitalized patients present with individual symptoms of conversion disorder, and approximately 5 percent of patients meet criteria for a full diagnosis of the condition. (Ali et al.) Treatment for individuals diagnosed with conversion disorder costs the United States approximately \$20 billion annually, not including disability payments and costs from missing work. (Ali et al.) This demonstrates the significant burden that conversion disorder places on both individuals and society, underscoring the need to find solutions to treat and prevent this condition.

Conversion disorder is a somatoform disorder characterized by physical illness symptoms with no biological explanation, and is usually due to psychological factors. (“Conversion Disorder”) While somatoform disorders include a broad range of physical symptoms, patients diagnosed with conversion disorder present with more neurological symptoms, including paralysis, sleep disturbances, seizures, weakness, or a lack of input from one or more senses. (“Conversion Disorder”) Very little research has been done on conversion disorder; there are no diagnostic tests, and it is thus a diagnosis of exclusion. (“5 Myths and Misconceptions About Conversion Disorder Debunked”) Because conversion disorder is a mental health condition, psychotherapy is often the first-line treatment. (“Conversion Disorder”) However, treatments are not always successful or definitive. Up to 25% of individuals diagnosed with conversion disorder have further episodes and symptoms despite receiving treatment. (Ali et al.) Due to the significant and recurring impacts of conversion disorder and lack of research, it is vital to dig deeper into the biological stances and find further solutions for this obscure disorder.

Exposure to Trauma in Conversion Disorder

The first step in discovering new treatment options for this condition is to gain a deeper understanding of its pathogenesis. However, the cause of conversion disorder is still unknown. One of the criteria for diagnosing this disorder is identifying physiological symptoms with no detectable causes. The prevailing theories about the cause of conversion disorder involve disrupted communication between the brain and nervous system.(Ali et al.) Conversion disorder symptoms have also been seen in individuals who have experienced recent trauma. For example, if someone witnesses a traumatic event, such as a car accident, they could start shaking uncontrollably. In a 2005 study, 54 patients with conversion disorder and 50 control patients were screened for life symptoms experienced within the year their symptoms began.(Roelofs et al.) Results highlighted a strong correlation between the recent life events and the severity of symptoms. Events related to work and relationships were linked with an even stronger connection to developing conversion disorder. While a history of trauma is common in conversion disorder patients, it is essential to note that the trauma does not have to be recent. In a 2017 study, 60 female patients between 18 and 65 years old who were diagnosed with conversion disorder were given childhood trauma questionnaires.(AKYÜZ et al., “Conversion Disorder Comorbidity and Childhood Trauma”) The questionnaire was used to screen emotional and physical neglect, as well as physical and sexual abuse before the age of 20.(AKYÜZ et al., “Conversion Disorder Comorbidity and Childhood Trauma”) The results of this study highlighted that a total of 70% of individuals diagnosed with conversion disorder were exposed to childhood trauma, with 53.3% of individuals exposed to physical violence and 25% exposed to sexual assault.(AKYÜZ et al., “Conversion Disorder Comorbidity and Childhood Trauma”) Therefore, this study demonstrates that trauma is highly associated with and a possible determining factor of conversion disorder diagnosis. These findings imply that early and recent trauma could both be a potential cause of conversion disorder.

Exposure to Stress in Conversion Disorder

It is common knowledge that exposure to traumatic events, both recent and further in the past, can lead to stress. The physical effects of stress can be severe. Stress is known to cause dizziness, shaking, and a weakened immune system. (“What Is Stress?”) Interestingly, highly stressful experiences are the most common causes of conversion disorder episodes.(“Conversion Disorder”) For example, this can be seen through the effects of the COVID-19 pandemic. In a 2021 study, researchers found that there was a 60.1% increase in patients diagnosed with conversion disorder during the pandemic.(Hull et al.) They hypothesized that this increase in diagnosis reflected the stressful events people experienced during this period.(Hull et al.) While there is some research showing the connection between stress and conversion disorder, there is limited information available due to the complexity of conversion disorder diagnosis and the wide range of symptoms. Therefore, to try to understand how stress may influence conversion disorder, we must examine research on stress and other psychological disorders that manifest physical symptoms. (“Overview”)

One such example is post-traumatic stress disorder (PTSD). In PTSD, individuals who have experienced severe trauma have persistent symptoms including sleep disturbances, fast breathing, and faster heart rates. (“Overview”) Research highlights that individuals diagnosed with PTSD are more susceptible to stress. (“Overview”) Similarly, patients diagnosed with PTSD are more likely to experience non-epileptic seizures than epileptic seizures after a stressful event. (Fisman et al.) This suggests that stress may be playing a role in the onset of non-epileptic seizures. A similar relationship may occur between stress and conversion disorder. While not directly researched, one of the criteria for the diagnosis of conversion disorder is non-epileptic seizures. (“Neurological Symptoms Are Real and Improvement Is Possible-Functional Neurologic Disorder/Conversion Disorder - Symptoms & Causes”) Given that there is precedent for stress-inducing non-epileptic seizures in PTSD patients, something similar may be happening in patients with conversion disorder. In addition, as stress can have a wide range of effects on the body, more than one physical symptom of conversion disorder could be due to stress. However, more research is needed to determine if stress is truly a cause of physical conversion disorder symptom onset.

Stress and the Microbiome in Conversion Disorder

While stress can directly impact many parts of the human body, it can also have indirect effects that affect health. The microbiome is an ecosystem of different microbes such as bacteria, protozoans, viruses, fungi, archaea, and more. Microbiomes play a considerable role in maintaining health, digestion, immunization, and other bodily functions. In a healthy person, microbes coexist peacefully, with many of them found in the intestines. The gut microbiome and stress are closely linked, each influencing the other. (“How Stress Affects the Microbiome (and Vice Versa)”) Gut microbes can influence the brain and mental health through bidirectional communication systems of the neural, immune, and endocrine pathways. (Clapp et al.) Gut bacteria changes can affect the production of neurotransmitters like serotonin and gamma-aminobutyric acid (GABA), which are essential for communication throughout the human body. (Chen et al.) Imbalances in the gut microbiome disrupt this communication and have been linked to the development of mental health disorders, including depression or anxiety. The microbiome mediates changes in mental health disorders through the gut-brain axis, or the signals that pass between the digestive and central nervous system. For example, the microbiome produces neurotransmitters, alters blood-brain barrier permeability, and more. (Liu and Zhu) As one of the possible contributing factors to conversion disorder is stress, it is important to consider the role of stress-induced microbiome changes in its onset. While there are many ways that stress can impact the intestine and the microbiome, large amounts of stress can lead to reduced protective mucus, increasing gut permeability. (Beurel) This results in a condition known as “leaky gut”, where bacteria can seep into circulation, causing inflammation. (Beurel) The release of cytokines is a sign of an inflamed microbiome and also influences brain function, leading to mental health illnesses, like anxiety and depression. In a 2017 study, a direct correlation between increased releases of cytokines and depression symptoms was established, indicating that the

stress placed on the microbiome plays a role in the symptoms of depression.(Clapp et al.) A connection between conversion disorder and elevated cytokines has also been seen.(Mark) Conversion disorder has a (17% to 44%) comorbidity with depression. Besides the gut, stress also impacts the microbiome itself. For example, in a 2017 study, chronically stressed mice had a drastic change in microbiota composition – specifically, a decrease in *Lactobacillus*.(Marin et al.) When increasing the levels of *Lactobacillus*, the mice’s behavioral abnormalities seemed to have improved.(Marin et al.) This study provides a scenario for how *Lactobacillus* can cause modifications in resilience during stressful situations. These findings highlight the impact that stress can have on the gut microbiome. While not directly tied to conversion disorder, this relationship emphasizes how stress can disrupt communication between the brain and the body. Just like how stress alters gut function, it may also trigger neurological miscommunications that underlie conversion disorder.

The connection between the microbiome and conversion disorder is hypothesized due to their overlapping features, such as the influence of neurotransmitters, the hippocampal expression of brain-derived neurotrophic factor (BDNF), and shared inflammatory responses.(Borrego-Ruiz and Borrego) Gut bacteria, such as *Candida* and *Lactobacillus*, monitor production of neurotransmitters including serotonin, GABA, and dopamine.(House) Altered microbiome composition can disrupt these signals, leading to glutamatergic and dopaminergic dysfunctions that align with common symptoms for conversion disorder. Microbiome health impacts hippocampal expression of BDNF, an important neurotrophin that supports neuronal survival and adaptability. In a 2007 study, conversion disorder patients’ BDNF levels were compared with healthy individuals’ levels. The results showed that healthy individuals had significantly higher levels of BDNF (31.4 +/- 8.8 ng/mL) than conversion disorder patients (24.3 +/- 9.0 ng/mL).(Deveci et al.) Because the health of the microbiome impacts the expression of BDNF, disruptions in the microbiome may worsen or contribute to these deficiencies. Another connection between microbiome and conversion disorder is proved by affected neural tissue from inflammatory cytokines. Dysbiosis causes toxins to seep into systemic circulation, activating inflammation. This inflammatory state increases the production of reactive oxygen species: highly reactive molecules that can damage proteins, lipids, and DNA.(Juan et al.) This process is relative to the brain as inflammation can disrupt the blood-brain barrier, allowing cytokines to affect neural tissue. Therefore, it is a possibility that the same inflammation-driven stress caused by gut dysbiosis may exacerbate the neural disruptions associated with conversion disorder. Beyond direct inflammation, dysbiosis also deregulates the hypothalamic-pituitary-adrenal (HPA) axis, causing significantly increased levels of cortisol – the body’s primary stress hormone. The increase in cortisol compromises the gut barrier, amplifies inflammatory signals, and disrupts nerve communication between the gut and the brain, creating a cycle of stress and neurological dysfunction.(Knezevic et al.) This evidence suggests that microbiome disruptions may act as a catalyst of the neurological symptoms observed in conversion disorder, highlighting the connection between both.

Genetic Factors and Conversion Disorder

It is important to note that while exposure to stress is thought to be a major contributing factor to conversion disorder, genetics may also play a role. This was shown in a 2017 study where 51.7% of the patients had a history of psychiatric disorders among their relatives.(AKYÜZ et al., “Conversion Disorder Comorbidity and Childhood Trauma”) Furthermore, evidence shows that conversion disorder is more prevalent in females than males, with over twice the number of women diagnosed with conversion disorder than men.(Chaudhry et al.) There has also been evidence that connects conversion disorder to a specific gene. In a study where 69 patients were genotyped for 18 single-nucleotide polymorphisms from 14 candidate genes, a tryptophan hydroxylase two gene polymorphism -G703T- seemingly predicted manifestations of conversion disorder.(Primavera A. Spagnolo et al.) The tryptophan hydroxylase two genotypes also showed a connection with childhood trauma, predicting more severe symptoms after trauma exposure.(Primavera A. Spagnolo et al.) Based on this evidence, genetics are likely to play a role in the development of conversion disorder. In addition, studies have also shifted focus to epigenetic mechanisms. Epigenetics is changing gene expression and translation without changing the DNA sequence. One example is cellular differentiation, where epigenetic mechanisms enable different cells to activate distinct sets of genes, forming specialized cell types.(Cell Differentiation | Description, Stages, Gene Expression, & Examples | Britannica) Outside triggers induce epigenetic changes, influencing behavior and disease resistance.(Ho et al.) For example, stress experienced in one generation can affect behavior and mental health in the next generation due to epigenetic modifications.(Jiang et al.) This can be seen in the well-documented Irish potato famine, where fat storage in kids was completely different from that of their mothers, who were pregnant during the famine, highlighting that stressful situations in one generation can impact the next.(King and Skinner) Similarly, studies have also found that biological sex is associated with epigenetic profiles, highlighting that epigenetic factors may influence the risk and severity of conversion disorder differently in males and females.(Primavera A Spagnolo et al.) These studies provide the foundation for a connection between genetics and conversion disorder, highlighting that genetics may also influence the risk for and onset of conversion disorder.

Current and Future Treatments for Conversion Disorder

Currently, the majority of treatments for conversion disorder include different types of therapy: cognitive behavioral therapy, physical therapy, and hypnotherapy.(“What Is Functional Neurological Disorder (FND)?”) However, these treatments are not always effective and they can even do harm to patients. Because conversion disorder is identified by physical symptoms with no biological explanation, medical providers may approach treatment as if the goal is to convince patients that nothing is truly wrong – despite the fact that the patient’s symptoms feel very real to them.(“What Is Functional Neurological Disorder (FND)?”) One possible treatment can be to reduce stress. Getting at least 7 hours of sleep, maintaining a healthy plant-based diet, exercising regularly, and maintaining a balanced social life are many ways to reduce stress.(Godman) By

practicing these healthy habits, individuals are able to approach challenging situations in a more positive way, leading to a decrease in stress.

Another possible treatment is to leverage the microbiome by a change in diet. Fermented foods like yogurt and kimchi provide beneficial probiotics that support the balance of the microbiome. Probiotics increase beneficial microbes, strengthen the gut barrier, and can prevent or cure dysbiosis.(Chandrasekaran et al.) Omega-3 fatty acids, found in salmon and walnuts, can also decrease inflammation in the microbiome by inhibiting pro-inflammatory mediators, like Lipopolysaccharide, and stimulating the production of anti-inflammatory factors, aiding in tissue repairment.(Chandrasekaran et al.) Prebiotic foods, including onions and bananas, also aid in keeping the microbiome healthy by supporting the growth of beneficial bacteria(ELS). By keeping the microbiome balanced and healthy, neural pathway communication will improve in conversion disorder patients, acting as a possible treatment for this condition.

Conclusion

Conversion disorder, a condition where physical symptoms are shown without biological explanation, remains a condition that has very little research about it, yet its impact on patients and society are immense. Research consistently shows that trauma, genetics, and stress may play a role in the onset of conversion disorder, and evidence portrays the microbiome as a key player in shaping brain function and stress responses. Dysbiosis, inflammatory cytokines, and neurotransmitter disruptions reveal a potential biological connection between psychological stress with neurological dysfunctions. Current therapies – while helpful for some – are not always effective and often risk invalidating patients’ feelings. Moving forward, treatment approaches should focus on leveraging the microbiome or finding beneficial ways in reducing stress. Ultimately, in order to approach conversion disorder in an effective way, research must be expanded not only to discover its biological underpinnings, but also to bridge the connection between the brain and body in treatment. Only through this integrative approach can we reduce stigma, improve patient outcomes, and begin to truly understand the complex interplay of biology and psychology that defines conversion disorder.

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A Quantitative Evaluation of Patient Preferences and Treatment Outcomes in Fixed Orthodontic Braces versus Clear Aligner Therapy (Invisalign) By Ahmed Ali

Abstract

Braces and Invisalign are two of the most popular ways of fixing malocclusions. The following article compares these two by reviewing clinical studies and using the 400 survey responses it received. The findings suggest that the choice of which orthodontic treatment to select should be guided by the severity of teeth alignment, comfort, and overall personal preference. Nevertheless, both treatments are, of course, better than no treatment and are effective in achieving better oral health.

Introduction

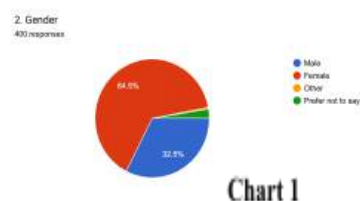
The purpose of orthodontic treatment is to make the best of your teeth (1), whether that be by clear aligners (e.g., Invisalign) or traditional braces, common among children to young adults. Invisalign, a treatment that uses clear, plastic aligners customised for each patient by a 3d scan in their mouth, however, is limited in terms of how many teeth can be moved at a time(2). Studies suggest fixed orthodontic treatments (braces) are more efficacious and can quite possibly even achieve a near-perfect result (2) yet patients are still turning to Invisalign in increasing numbers and its popularity at an all-time high. Furthermore, as of 2023, over 17 million patients have received Invisalign treatment (3) a number that evinces a major shift in not only orthodontic preferences but society's attitude towards prioritising aesthetics, comfort and flexibility. Moreover, Invisalign isn't only a lifestyle fit, but it also promises perfect teeth without the constant presence of metal brackets, which can possibly exacerbate the fragile self-esteem of today.

We see countless studies on the internet discussing which one is better, braces or Invisalign, which one looks better, braces or Invisalign. Still, we don't see full reports on actual patient experiences, such as comfort, treatment duration, the reason for choosing their orthodontic treatments, whether that be personal or doctor recommendation. In addition, there is almost no research analysing whether gender might have a role to play in orthodontic treatment, also if gender might be linked to the reason the user would choose their preferred treatment.

This study addresses the gaps we currently have in our knowledge – after all, to famously quote Albert Einstein, “If we knew what it was, we were doing, it would not be called research, would it?”(4). Appearances and orthodontist recommendations will be the largest reasons for choosing a treatment. Invisalign users are more satisfied with the level of comfort. More females will have had orthodontic treatment in general. Braces will be longer in terms of treatment duration between the two.

Results

In total 400 responses were gathered. Out of the 400: 258 were female, 130 males, 10 prefer not to say,



and 2 others (Chart 1). Out of the 258 females: 21 had Invisalign, 135 had braces, 84 had neither and 18 had both. Out of the 130 males: 13 had Invisalign, 58 had braces, 51 had neither and 8 had both. In the other category, had Invisalign and 1 had both. Prefer not say category contained 6 braces and 4 did not have either (Table one).

Count of 3. Have you used either braces or invisalign		Column Labels				
Row Labels		Yes, I've had invisalign	Yes, I've had braces	Not had either	Both	Grand Total
Female		21	135	84	18	258
Male		13	58	51	8	130
Other		1			1	2
Prefer not to say			6	4		10
Grand Total		35	199	139	27	400

Table 1

The same confidence interval was used for all calculations, CI:95%. Out of the 27 individuals who had experienced both, a majority 63% $\pm$ 18.2% said that Invisalign was more comfortable for daily wear and 25.9% $\pm$ 16.5% reported that braces were more comfortable and a minority of 11.1% $\pm$ 11.9% felt that there was no difference (chart 2).

8. How often did you experience pain or discomfort during your treatment?
35 responses



Chart 2

5. Which treatment was more comfortable for daily wear?
27 responses

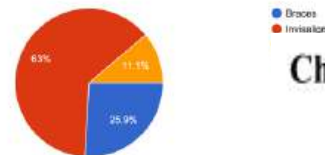
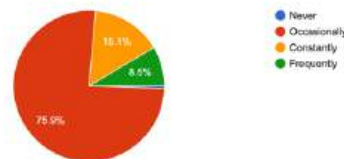


Chart 3

Individuals who had just got braces or Invisalign were asked the same question: "How often did you experience pain or discomfort during your treatment?" (Appendix A.2, Appendix A.3). Out of 35 responses for Invisalign, 8.6% $\pm$ 9.3% say never, 62.9% $\pm$ 16.0% occasionally experienced pain, 14.3% $\pm$ 11.6% were constantly in pain, and 14.3% $\pm$ 11.6% went through discomfort frequently (Chart 3).

Chart 4

8. How often did you experience pain or discomfort during you
199 responses



Similarly, those who got just braces were asked the same thing, however, with a larger number of individuals (199). 1% $\pm$ 0.98% of the sampled population of only braces never experienced pain, 75.9% $\pm$ 5.9% reported they felt occasional pain, 15.1% $\pm$ 5.0% believed it to be consistent and 8.5% $\pm$ 3.9% frequently experienced pain (chart 4).

Chart 5

7. How long did your treatment last?
196 responses

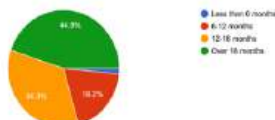
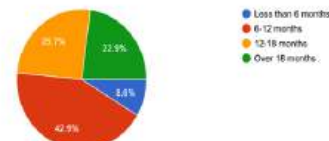


Chart 6

7. How long did your treatment last?
35 responses



Respondents of either just braces or Invisalign were asked a question on the length of treatment (How long did your treatment last (Appendix A.2, A.3). Invisalign responses were as follows: <6 months 8.6% $\pm$ 9.3%, 6-12 months

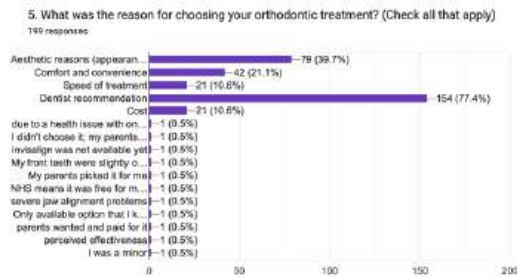


Chart 7

specifically braces, the majority chose braces due to a dentist's recommendation at $77.4\% \pm 5.8\%$, followed by aesthetics at $39.7\% \pm 6.8\%$, and the third largest reason was comfort and convenience at $21.1\% \pm 5.7\%$ (chart 7).

The data for Invisalign, however, came out to be what was expected, with the majority of reasons being

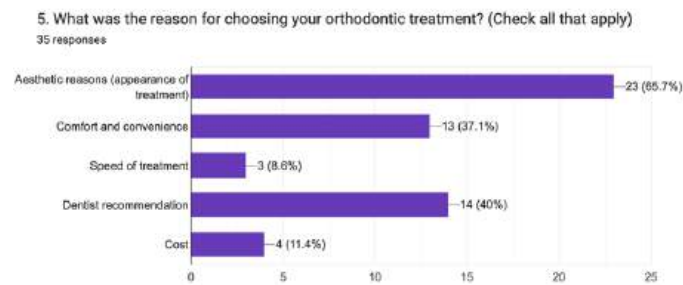


Chart 8

aesthetics at $65.7\% \pm 15.7\%$, followed by dentist recommendation at $40\% \pm 16.2\%$ and comfort and convenience at $37.1\% \pm 16.0\%$ (Chart 8).

M	N	O	P	Q	R	S	T	U	V	W	X
Observed (C)	Invisalign	Braces			Expected (E)	Invisalign	Braces		(O-E) ² /E	Invisalign	Braces
Female	39	153	192		Female	41.290323	150.70968		0.1270413	0.0348058	
Male	21	66	87		Male	18.709677	68.290323		0.2803671	0.0768129	
	60	219	279								
									χ^2	0.5190271	
									df	1	
									p-value	0.471257	

Table 2

The survey respondents were largely female, comprising 64.5% of the demographic, with 32.5% male, a minority of others at responses 0.5%, and a preference not to say at 2.5%. Furthermore, results were also analysed using Excel to show the quantity of which gender that chose said treatment. Invisalign only results: $8.14\% \pm 3.3\%$ for females and $10\% \pm 5.2\%$ for males, Braces only results: $52.3\% \pm 6.1\%$ for females and $44.6\% \pm 6.1\%$ for males (Table 1). Then, a chi-square test of independence was conducted to examine the relationship between gender and chosen orthodontic treatment. (Both 'not added' and 'prefer not to say' were excluded from the orthodontic treatments, as were others, to avoid skewing the results.) The relation between these variables was not significant, $X^2(1, N = 279) = 0.519$, $p = 0.471$; therefore, the results are not

statistically significant at $p < 0.05$ (Table 2), suggesting there is no correlation between gender and chosen orthodontic treatment.

Individuals who had both forms of treatment were asked which treatment gave them better results in terms of teeth alignment. results were as follows: braces 70.4% $\pm$ 17.2%, both were equally effective 22.2% $\pm$ 15.7% and Invisalign 7.4% $\pm$ 9.9% (Chart 9).

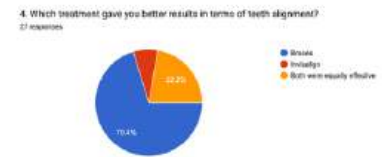


Chart 9

Discussion

This study examined several factors that could affect one's choice of orthodontic treatment. This study suggests that Invisalign is significantly more comfortable overall than braces for daily wear which might link to the result where individuals who had both braces and Invisalign were asked at the end of the survey if they had to choose one out of either braces or Invisalign which one would they choose with a majority choosing Invisalign at 66.7% $\pm$ 17.8% compared to braces 33.3% $\pm$ 15.6% (chart 10)

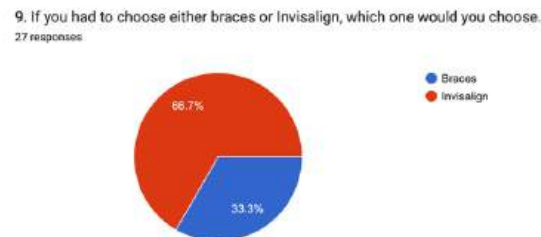


Chart 10

An inference made is that one of the largest reasons individuals choose braces is due to a dentist's recommendation, statistically significant, in contrast to patients picking Invisalign, where the dominating factor was aesthetics, suggesting that Invisalign is a treatment picked more out of preference. This was expected, as past studies have also shown a significant correlation between Invisalign and the primary factor for choosing it, aesthetics. However, even so, the data still also suggests that patients value the role of professional input.

Furthermore, the majority of both groups reported some sort of occasional pain, upholding the fact that some sort of pain or discomfort will occur no matter the treatment. Despite Invisalign users reporting more frequently of never experiencing pain compared to braces, the wide confidence intervals due to the small number of Invisalign users cause overlap, thus not allowing indication of strong statistical significance, thereby suggesting the results could be due to chance. Overall, the data suggests that the range of pain is similar for both Invisalign and braces groups; however, a larger sampling size would be needed to provide more evidence for a stronger conclusion.

A hypothesis made was that females in general would be more likely to choose either braces or Invisalign, a theory supported by previous research and studies taken. To test this, a chi-square of independence was taken, and it was concluded that the relationship between these variables was not statistically significant. This means that within this sample, males and females were equally likely to have chosen braces or Invisalign. A surprising result, however, could possibly be because the Invisalign group was a very small sample size, reducing statistical power.

But, even so, not significant, it might be a small indicator that, potentially, males are beginning to care more about their dental health, which is a trend worth looking into for the future.

Moreover, those who received both braces and Invisalign showed statistically significant results, indicating that Invisalign is far more comfortable than braces for individuals who had experienced both orthodontic treatments. This does, in fact, align with past studies which also indicate that Invisalign is superior in terms of comfort, however a potential reason for this might be that Invisalign is usually used on those who have less severe malocclusions and so braces are used on more severe cases and therefore to re-align more severe cases the pain threshold would be higher, a theory that might warrant a study to take place.

In addition, the results of this group indicated with statistical significance that braces almost always give better terms of teeth alignment, if not the same. Of course, this corresponds to previous data showing that braces are superior in terms of actual teeth alignment results.

The sampling platform used Survey Swap allowed for quick responses in a fairly short period of time and was one of the only ways the sole researcher could see to gather data. Nevertheless, this does not take away from the fact that, as a surveyswap was used; as a result, limitations were imposed. Honesty was one of them, as respondents potentially could have lied on the survey to receive the benefits of the survey website. Moreover, it caused an imbalance in the sample population, with the majority demographic being female and having a very small population of those who had Invisalign. As we progress further, a new study could be done using actual clinical data and surveys given to patients at said clinic to ensure honesty, reduce bias and overall improve the research, ergo improving the accuracy of data.

Considered collectively, these findings coalesce to show that both orthodontic treatments of braces and Invisalign are excellent treatments but the one you choose is dependent on your needs and wants, Braces when considered with all its pros and cons is indeed less comfortable, more time consuming and possibly more painful however this doesn't take away from the fact that braces will leave you with better results and is the ultimate form of treatment when it comes to fixing severe cases of malocclusions however, if what you seek is a more comfortable, more manageable, and the case is less severe Invisalign almost definitely is the superior choice. At the end, the one you choose needs to match you. The results further corroborated the idea that the majority reason Invisalign is chosen is due to aesthetics, suggesting individuals care more about appearance than the final overall result, a trend/idea that is worth looking into more alongside the psychology behind it.

MATERIALS AND METHODS

After careful deliberation and evaluation of several survey platforms, Google Forms was selected for multiple reasons: customisation, reliability, and ease of access, to name a few. Subsequently, a survey was then created using Google Forms, questions began in asking respondents of their gender and age (Appendix A) and then would split into three different categories of questions, conditional to their response of question 3 (Have you used either braces or Invisalign), with answers being Yes, I've had braces, Yes, I've had Invisalign, Both or Not had

either. For example, if respondents were to choose Yes, I've had braces, they would be taken to the braces set of questions (Appendix A.3), and so forth (Yes, I've had Invisalign – Appendix A.2, Both – Appendix A.1 and if not had either was selected, the form would end). Respondents who had chosen just braces or Invisalign were essentially asked the same questions but in different sections to optimise data analysis and interpretation, in contrast to those selecting both, who would have gotten a different set of questions, more directly comparing and contrasting the two different options, whereas the other two sets are focused on personal experiences and satisfaction with their chosen treatment.

In an ideal scenario, preferably, the respondents were to be found from a random sample of students at school or patients at a dental clinic to increase validity and allow for a more controlled experiment however due to the authors' recent relocation to the United States in February and had not enrolled in school until August, convenience sampling was used through the website Survey Swap since other forms of sampling was not feasible at the time. Survey Swap is an online surveying platform that uses voluntary participants to answer surveys of those who need respondents.

Questions ranged from asking individuals who had both braces and Invisalign which treatment gave them better results in terms of teeth alignment (Appendix A.1) to asking if they had to choose either braces or Invisalign, which one they would pick. In comparison to the specific braces or Invisalign categories, questions were asked differently. In the braces or Invisalign categories, factors for choosing one's orthodontic treatment were assessed, with answers being aesthetics, comfort, speed, dentist recommendation, and all the way to cost. Data collected was then analysed using Microsoft Excel to assess relationships. Chi-square test of independence was used to show statistical significance.

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Medical Pluralism in South Asian Communities By Saanvi Gudapati

Introduction

In many South Asian communities, the doctor's office is not the only place where healing takes place. A grandmother's herbal concoction for a lingering cough, a temple priest's blessing for a complicated pregnancy, and a pharmacy prescription from a Western-trained physician for hypertension may all simultaneously exist in the same patient's health routine. This coexistence and interaction of distinct medical systems, each with its own cultural grounding and modes of practice, is known as medical pluralism. Medical pluralism recognizes that societies often have more than one way to understand and treat illnesses or medical conditions. In South Asia and its diasporas, it is more than an academic concept: it is a lived reality shaped by history, migrations, and the complex interplay between tradition and modernity.

For centuries, India and other regions have been known for their popular use of traditional medicinal practices known as Ayurveda, Yoga, Unani, Siddha, Sowa-Rigpa, and Homeopathy, which are collectively termed the AYUSH systems (Ministry of AYUSH). These long-established systems have been integral to health care across South Asia, and their principles are deeply intertwined with community trust, culture, and spiritual beliefs. With colonization and the subsequent globalization of biomedicine, these systems were not erased but rather layered alongside Western medical approaches, creating a unique and sometimes poorly integrated pluralistic medical landscape (Leslie).

Today, this pluralism has taken on new dimensions. In urban centers such as Delhi, Mumbai, and Dhaka, patients often navigate between government hospitals, private clinics, and more traditional routes, selecting treatments based not only on perceived effectiveness but also on affordability, accessibility, and cultural values ("Integrating Traditional and Modern Healthcare Systems"). In diaspora communities from Toronto to London to New Jersey, these challenges are further exacerbated by the difficulties of immigration: language barriers, limited insurance coverage, and the desire to maintain a connection to one's cultural heritage ("Integrating Traditional and Modern Healthcare Systems"). Thus, the decision to seek multiple forms of care is not rash but instead informed by layered understandings of illness that account for both the physical body and the social, spiritual, and emotional self.

Examining medical pluralism in South Asian communities therefore requires attention not only to the medical systems themselves but also to the sociocultural, economic, and political forces that shape how they are used and implemented ("Integrating Traditional and Modern Healthcare Systems"). It is in these intersections—where a patient's cultural identity meets the institutional structures of health care—that the most revealing patterns emerge. This paper explores those intersections, analyzing how South Asian communities navigate and negotiate among diverse healing systems, the factors that guide their medical decision-making, and the implications for health outcomes in increasingly multicultural societies.

Colonial and Postcolonial History of Medical Pluralism

The pluralistic medical environment of South Asia cannot be understood without tracking its colonial and postcolonial history. Before European intervention, South Asia was already home to diverse and sophisticated healing systems, most prominently the AYUSH systems, each rooted in longstanding religious and cultural traditions (Sharma). Ayurveda, with origins traced to the Vedic texts and its classical literature, including the Charaka and Sushruta Samhitas, was long regarded as divine knowledge passed from gods to sages (Pandey, Rastogi, and Rawat). It is heavily woven into Hindu cosmology and daily life, reflecting a holistic philosophy of balancing the five elements and three doshas. Up to 80% of people in India and Nepal report using Ayurvedic treatments, demonstrating its endurance within community and spiritual life (Pandey, Rastogi, and Rawat).

Unani medicine originated in ancient Greece from Hippocrates and Galen and spread via Arab-Persian scholars. Introduced into South Asia by the seventh century, it flourished under medieval Muslim rule. Mughal emperors notably patronized Unani hospitals and scholars, blending it with local Indian medical ideas (Rahman). While less prevalent today than Ayurveda, Unani is recognized by the Indian government as a legitimate traditional system. Siddha medicine arose in South India, chiefly Tamil Nadu, and likewise claims divine roots (Samal). Historically, Siddha was practiced by itinerant siddhars (seer-healers) who trained disciples through a guru-shishya lineage. Even under colonialism, tens of thousands of traditional healers provided the bulk of rural care (Gautham et al.).

With the advent of British colonial rule in the eighteenth and nineteenth centuries, Western biomedicine was elevated while indigenous systems were marginalized (Harrison; Arnold). Colonial authorities established hospitals and medical schools primarily to serve European troops and administrators, and policies prioritized Western science education over classical Indian learning (Kumar). Traditional healers, who treated “about eighty percent of the people,” were regarded as “untouchables of the profession” by the colonial medical establishment (Jeffery). Registration laws even barred most Ayurvedic and Unani practitioners from formal practice (Bala). Western public health campaigns expanded vaccination and sanitation with little regard for local customs, framing science as modern and universal while branding traditional methods as inferior.

Post-independence governments sought to redress this imbalance, culminating in the 2014 creation of the Ministry of AYUSH, which oversees the education, regulation, research, and promotion of these traditional systems (Ministry of AYUSH). While the ministry has boosted funding and international visibility, critics argue it often prioritizes commercial promotion over integration into public health (Samal). Despite its symbolic break from colonial hierarchies, biomedicine remains the benchmark in India’s healthcare system.

Sociocultural Dynamics in Contemporary Medical Pluralism: Identity and Gender

In both South Asia and its diaspora, healthcare choices are deeply shaped by sociocultural identity and gender roles (Ernst). Illness is often understood holistically, encompassing both

physical and social dimensions, and these interpretations influence the therapies pursued (Fikree and Pasha). Family and community elders play a central role in medical decision-making, and rituals such as visits to pilgrimage sites, herbal remedies recommended by grandmothers, or guidance from local hakims continue alongside biomedical interventions (Grzywacz et al.). Generational factors also shape pluralistic practices. First-generation immigrants often retain home-country habits, including Ayurvedic home remedies or consultations with ethnic practitioners for musculoskeletal or dietary issues (Grzywacz et al.).

Gender roles strongly mediate pluralistic health-seeking behavior. Women often act as caretakers and custodians of folk medical knowledge (Siva et al.). Mothers and grandmothers administer herbal concoctions for colds or postpartum therapies and frequently coordinate care through local midwives or female healers. Both men and women prefer healthcare providers of their own gender for sensitive conditions (Siva et al.). Religious and caste identity further influence pluralism, with patients often selecting healers who share their faith or community background (Ernst; Siva et al.).

Economic Factors and Healthcare Constraints

Economic constraints and healthcare infrastructure critically shape pluralistic medical practices in South Asia (Gideon, Asthana, and Bisht). Out-of-pocket spending dominates health financing in the region, making cost a decisive factor in treatment choices (Sriram and Albadrani). Traditional medicine, including AYUSH systems and home remedies, often fills critical gaps as herbal remedies, yoga, and locally prepared treatments are inexpensive or free (Rudra et al.; Montesi et al.; Shrivastava, Shrivastava, and Ramasamy). The Indian government has attempted to institutionalize traditional medicine by installing AYUSH units in primary health centers, though research indicates these placements often function as “stand-ins” covering physician shortages rather than fully integrating plural care (Shrivastava, Shrivastava, and Ramasamy). Regional variation further shapes pluralism, with states like Kerala demonstrating higher utilization due to stronger local roots and cultural familiarity (Rudra et al.).

Government Role and Policy

The Indian government has actively shaped medical pluralism through the Ministry of AYUSH, established initially in 2003 and elevated to full ministry status in 2014 (Ministry of AYUSH). The ministry aims to mainstream local health traditions and complementary medicine into the healthcare system (Bajpai; Government of India). Integration efforts include the co-location of AYUSH practitioners in primary health centers alongside allopathic doctors, and pilot programs have trained health workers in Ayurvedic first aid (Saxena et al.). Globally, India certifies foreign practitioners in Ayurveda and Yoga and promotes medical tourism centered on traditional therapies (India, Times of). Despite these efforts, challenges remain, including prioritization of promotion over clinical rigor, inconsistent quality standards, and gaps in rural access (Anshu and Supe).

Conclusion

Medical pluralism in South Asian communities is neither incidental nor peripheral; it is a primary logic for how people interpret illness, seek care, and make therapeutic choices. Pluralism is rooted in layered histories, especially the colonial reordering of medical authority that elevated Western biomedicine and relegated indigenous systems, shaping perceptions of legitimacy and access today (Mishra and Nambiar). Economic and infrastructural realities make pluralism practically necessary for millions. High out-of-pocket spending, gaps in primary care, and the relative affordability and cultural accessibility of AYUSH and home remedies mean that people often combine modalities not as ideological preference but as pragmatic coping strategies (Kumar et al.; Zhang, Xue, and Fong).

If pluralism is to improve health outcomes rather than merely reflect constraints, three priorities stand out. First, build evidence-sensitive integration by investing in culturally aware clinical research and pharmaco-epidemiology for herbal products and combined regimens (Zhang, Xue, and Fong). Second, strengthen systems at the primary-care level, resourcing PHCs and formalizing referral mechanisms between AYUSH and allopathic providers. Third, cultivate cultural competence in diaspora and mainstream settings so that clinicians coordinate care and treat patients' cultural practices as data in clinical decision-making.

Finally, any durable reform must reckon with political history. Decolonizing health policy means acknowledging past marginalization, restoring institutional voice to indigenous practitioners, and building regulatory frameworks that respect cultural sovereignty while protecting public health. When policy makers, clinicians, and communities engage in evidence-informed dialogue, medical pluralism can become a resource for more inclusive, equitable, and resilient health systems across South Asia and its diasporas.

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Supervised and Unsupervised Machine Learning to Predict Groundwater Quality: Telangana Case Study By Daria Stoyanova¹¹⁹ and Abdulla Kerimov¹²⁰

Abstract

Accurately predicting and understanding the features that impact groundwater quality is imperative to various regions across the world. Especially semi-arid regions, like Telangana State, India, that rely on irrigation for agriculture, knowing whether groundwater quality is up to standard is critical. To predict groundwater quality faster than existing methods, we utilized supervised and unsupervised machine learning models. Our best supervised model, hyperparameter tuned Random Forest, had test f1 scores for two of our three quality labels of 0.87 and 0.91 with no indication of under or overfitting. On the other hand, our best unsupervised model, Spectral Clustering, qualitatively compared very consistently with our true labels. Our unsupervised results come from our implementation of the Elbow method, an algorithm applied with KMeans that demonstrated to us between two and four clusters were ideal for our dataset. Furthermore, our SHAP analysis indicated HCO₃, Mg, and SAR to be the features that impact quality classification the most amidst all three quality labels. Interestingly, SO₄ was the feature that impacted our second quality classification the most - revealing that it can also play an important role in groundwater quality.

Keywords groundwater quality, irrigation system, chemical and physical properties, machine learning, supervised learning, unsupervised learning, feature importance analysis, SHAP

Introduction

Water is critical to sustaining life, yet its importance to the health of livestock and crops can often be overlooked. Consumption of low-quality water harms crops, leading to failure and the spread of disease among livestock. Furthermore, water used in agriculture for produce has been found to be a source of pathogens that can cause contamination among humans (1). The demand for land for cultivation and water for irrigation has reached a peak as food consumption is at its highest (2). Yet, numerous industrialized countries are experiencing water overuse - consumption beyond the natural replenishment rate. Such overuse harms irrigation systems and causes increased salinity, among a myriad of negative effects like nutrient pollution and loss of plains and wetlands (3).

Irrigation is commonly practiced in arid regions of the world to grow crops by supplementing a lack of rainfall. However, the groundwater used for irrigation often contains more salts because of salt leaching in the soil surface and minerals that dissolve naturally as they reach the groundwater basin (4). High salinity in the water - and therefore soil - harms plants. Drought stress is increased, water conductance, soil porosity, and aeration are all limited. Extreme levels of salt can even cause a destruction of all vegetation. This creates the problem of limited choice among growers, as they are forced to select salt-tolerant crops (5). The state of Telangana,

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India, relies on such systems of irrigation. It plays a vital role in providing reliable water to support agriculture and crop cultivation for the more than thirty million people that reside on its borders (6). Therefore, ensuring the quality is up to standard is critical for the livelihood and prosperity of the state.

Traditional water quality monitoring has three main avenues: on-site sample collection, rapid on-site testing, or automatic monitoring stations. On-site sample collection is accurate but increases both cost and time. With rapid on-site testing, time is reduced, but so is accuracy as less metrics are taken into account. Lastly, automatic monitoring stations have limited coverage and are greatly expensive (7). Machine learning methods bring a novel and much more efficient way to assess such quality. Models can account for complex data and predict quality quickly based on low-cost physical and chemical composition of samples (8). Ultimately, with comprehensive datasets, they can lessen the challenges posed in regions like Telangana where predicting quality can be difficult among intensive agriculture practices (9).

Divy Jot (10) replicated water quality analysis that was previously done using linear regression with stack model and machine learning algorithms. They had a variety of strong results using Random Forest, Light Gradient Boosting Machine (LGBM), and Artificial Neural Network (ANN) Algorithms, all with accuracy above 95%. However, classifications of a marginal class using Random Forest had a recall of 42% and a f1 score of 56%. Similarly, there was low recall, 58%, when using LGBM.

Chinmayee Senapati et al. (11) used the stacking ensemble method to enhance the accuracy of groundwater quality prediction and offer spatial insights to identify areas susceptible to contamination. They implemented various clustering models such as KMeans, Gaussian Mixture Model (GMM) and Density-Based Spatial Clustering of Applications with Noise (DBSCAN). However, their silhouette scores of clustering with GMM and DBSCAN were 0.25 and 0.12, respectively, meaning clusters overlapped or were unclear.

Preet Singh et al. (12) used LGBM and CatBoost algorithms to categorize the quality of water suitable for agriculture purposes. Their overall accuracy of LGBM was 93% and CatBoost was 94%, but recalls of 86% and 89% respectively. However, inputs excluded pH, EC, SAR, and numerous dissolved ions, as high correlations increase risk of false model predictions. Realizing that amidst strong accuracies, previous works had low f1 scores, silhouette scores, or even exclude too many metrics with their inputs, we aim to build models with strong results for each quality class that use as many chemical metrics as possible without data leakage.

The objective of this study is to determine a way to understand and predict water quality for agricultural purposes without relying on the factors that directly classify it, such as salinity and sodium. Our aim is to build a machine learning model that can establish and increase knowledge on suitable crops and soil for varying water qualities. Specifically in regions like Telangana, such knowledge is immensely valuable to farmers, and ultimately the many who will consume the crops that are farmed. With both a supervised and unsupervised approach, we are striving to make accurate predictions and discover the features that greatly impact quality. Ultimately, by understanding the basis of where quality predictions come from, we can establish

the most important quality control metrics and achieve an accurate, fast, and reliable method in predicting the suitability of water samples.

Dataset

Our dataset includes 3 years (2018, 2019, 2020) of data on groundwater found in the Telangana state of India during the post monsoon season. The data was collected from Telangana Open Data portal, Telangana State, India and contains samples tested from various districts (13).

2018 contains 374 samples, 2019 contains 364 samples, and 2020 contains 368 samples for a total of 1137 samples. The data has 25 columns - 6 being descriptive identifiers: district, mandal, village, latitude, longitude, and season as shown in Table 1. 17 columns are related to chemical factors: groundwater level, pH, electrical conductivity (EC), total dissolved solids (TDS), total hardness (TH), RSC, SAR, and the amount of carbon dioxide, bicarbonate, chloride, fluoride, nitrate, sulfate, sodium, potassium, calcium and magnesium present in each sample as shown in Table 1.

The dataset has a Classification column, based on 9 classes - C1S1, C2S1, C3S1, C3S2, C3S3, C4S1, C4S2, C4S3, and C4S4 - that tells us how suitable water is for irrigation and crops. C1S1 are low salinity and low sodium waters that can be used well for irrigation and with most crops. C2S1 are medium salinity and low sodium waters that are suitable for irrigation and can be used on almost all soils with a low risk of development of harmful levels of exchange sodium. C3S1 are high salinity and low sodium waters that need good drainage and crops with strong salt tolerance. C3S2 are high salinity and medium sodium waters that need good drainage and should be used on textured or organic soils with good permeability. C3S3 are high salinity and high sodium waters that need special soil management, good drainage abilities, high leaching, and organic matter additions. C4S1 are very high salinity and low sodium waters that are not suitable for irrigation unless the soil is permeable and there is adequate drainage. C4S2 are very high salinity and medium sodium water not suitable for irrigation on fine textured soils, but can be used for irrigation on coarse textured or organic soils with good permeability. C4S3 are very high salinity and high sodium waters that produce harmful levels of exchange sodium in most soils and therefore require special management and good drainage. The final class, C4S4, are very high salinity and very high sodium waters that are generally unsuitable for irrigation purposes.

Table 1: Data description

Variable Name	Variable Description
district	District
mandal	Mandal
village	Village
lat_gis	Latitude
long_gis	Longitude

gwl	Groundwater level
season	Post monsoon
pH	Hydrogen ion concentration measuring acidity
E.C	Electrical Conductivity (dS/m)
TDS	Total amount of dissolved substances (mg/L)
CO3	Carbonate present (mg/L)
HCO3	Bicarbonate present (mg/L)
Cl	Chloride present (mg/L)
F	Fluoride present (mg/L)
NO3	Nitrate present (mg/L)
SO4	Sulfate present (mg/L)
Na	Sodium present (mg/L)
K	Potassium present (mg/L)
Ca	Calcium present (mg/L)
Mg	Magnesium present (mg/L)
T.H	Total hardness measuring total amount of calcium and magnesium ions (mg/L)
SAR	Sodium absorption ratio measuring sodium content relative to calcium and magnesium (meq/L)
RSC meq/L	Sum of calcium and magnesium concentrations subtracted from sum of bicarbonate and carbonate concentrations measuring potential sodium hazard (meq/L)
Classification	C1S1 (usable for irrigation), C2S1 (usable for irrigation), C3S1 (requires good drainage), C3S2 (requires drainage and permeability), C3S3 (requires special management), C4S1 (unsuitable for irrigation), C4S2 (unsuitable for irrigation), C4S3 (unsuitable for irrigation), C4S4 (unsuitable for irrigation)

Exploratory Data Analysis

In this section we explore the dataset to gain insight into various trends, patterns, and correlations. We utilized exploratory data analysis to discover relationships within our data, specifically between chemical composition and quality classification. We explored patterns between chemicals such as sodium, chloride, and bicarbonate, along with other measurements including EC, TDS, and TH, and that sample's quality classification.

Figure 1 illustrates the distribution of counts by classification labels for irrigation and crops. As seen in the graph, the vast majority of water samples (~580) are classified as C3S1 - high salinity and low sodium waters that require good drainage and crops with salt tolerance. A significant number of samples, around 200, are classified with C2S1, meaning they are medium

salinity and low sodium waters that are good for irrigation and can be used on almost all soils with a low risk of harm. A little less than 100 samples are notably classified as C4S1, with very high salinity and low sodium therefore not suitable for irrigation unless the soil is permeable and there is adequate drainage. The remaining six classes, C4S2, C3S2, C4S4, C4S3, C1S1, and C3S3, range greatly in their salinity, sodium, and suitability for irrigation. However, as samples with those classifications are so few - some with less than ten - demonstrates our dataset is greatly imbalanced. Because of this, when modeling, grouping classes together will be necessary to ensure realistic predictions.

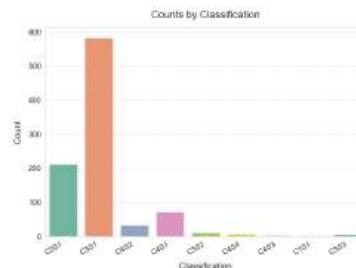


Figure 1: Count distribution of water quality classification labels for irrigation and crops.

The labels shown in Figure 1 were arranged into three groups. Figure 2 illustrates the distribution of counts by this necessary grouping to account for our imbalanced dataset. The first group is “Suitable for All Soils”, consisting of C1S1 and C2S1. Classes C3S1, C3S2, and C3S3 form the second group, “Requires Drainage + Management” - water suitable for irrigation but requires management and drainage, along with salt tolerant crops and permeable soil. The remaining classes are unsuitable for irrigation - C4S1, C4S2, C4S3, and C4S4 creating the final group, “Unsuitable”. Using that classification, there is still an imbalanced data set, but much less than using all 9 classifications.

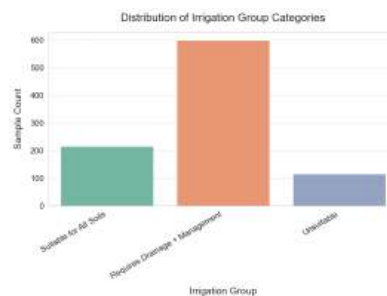


Figure 2: Count distribution of grouped water quality labels for irrigation and crops.

Figure 3 is the Spearman correlation matrix between variables. The correlation matrix illustrates notably high correlations between many variables, both negative and positive. For example, EC and TDS have a correlation of exactly 1, and EC and chloride have a high correlation of 0.91. Chloride and sodium also have a correlation of 0.73. TH has a strong correlation with EC (and therefore also TDS) of 0.83. Additionally, TH has a correlation of 0.79 with chloride. Aside from these 5 highly correlated features, the remaining features' correlation

coefficients have an absolute value of less than 0.8, demonstrating no strong evidence of high collinearity.

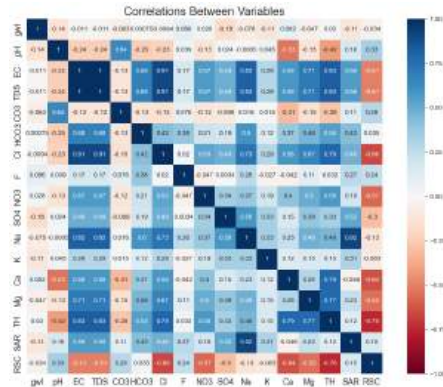


Figure 3: Spearman correlation matrix between variables.

Figure 4 shows the distribution of the amount of bicarbonate by the irrigation group. Samples with 0 to about 160 mg/L of bicarbonate typically belong to “Suitable for All Soils”. Samples with between 160 to around 500 mg/L of bicarbonate vary with belonging to each group, but the majority tends to belong to “Requires Drainage + Management”. 500 mg/L and higher samples tend to belong to the group “Unsuitable”, but similarly there are such samples classified as “Requires Drainage + Management”.

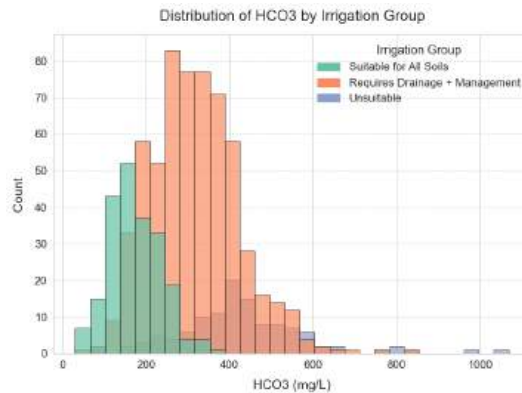


Figure 4: Distribution of bicarbonate by irrigation group.

Figure 5 shows boxplots of each of the three irrigation groups with respect to sodium content. Based on the boxplots, it is evident that irrigation groups are heavily reliant on sodium. “Suitable for All Soils” has the least variety, with most samples having strictly between 0 and 100 mg/L of sodium. The group “Requires Drainage + Management”, has more variety, with sodium presence ranging from 0 to around 250 mg/L, but outliers that reach past 400 mg/L. Finally, “Unsuitable” has the greatest variety, stretching from around 100 to over 700 mg/L of sodium present.

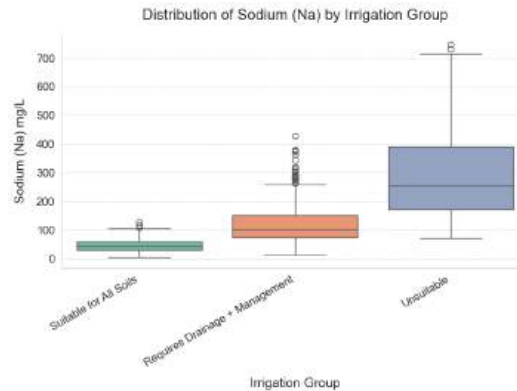


Figure 5: Boxplot of irrigation groups with respect to sodium content.

Figure 6 shows boxplots of irrigation groups with respect to the amount of chloride present. There is a strong trend visible between irrigation groups and chloride content. “Suitable for All Soils” has chloride composition ranging from 0 to around 150 mg/L. The group “Requires Drainage + Management” has a greater range of chloride present, from 0 to around 500 mg/L. The greatest variety of chloride present, from around 100 mg/L to outliers that go up to 2500 mg/L is the “Unsuitable” group.

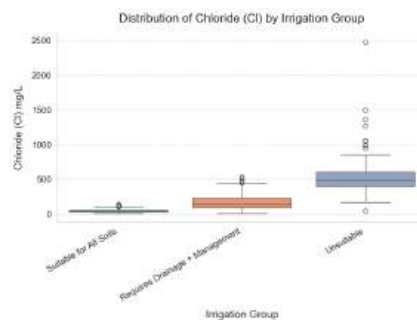


Figure 6: Boxplots of irrigation groups with respect to the amount of chloride content.

Figure 7 shows the scatterplot of sodium present versus EC, color coded by irrigation groups. The scatterplot illustrates a strong, positive, and linear correlation between sodium and EC. Furthermore, the scatterplot demonstrates a relationship between sodium, EC and the irrigation group. Samples with sodium levels between 0 to 150 mg/L and EC between 0 and 1000 dS/m tend to belong to the group “Suitable for All Soils”. Samples with sodium levels from 0 to around 400 mg/L and EC levels from 100 to around 2000 dS/m, are generally part of “Requires Drainage + Management”. Lastly, samples that belong to the group “Unsuitable” have the greatest range, of both amount of sodium and EC but EC levels strictly above 2000 dS/m, and sodium levels anywhere from around 75 to over 700 mg/L.

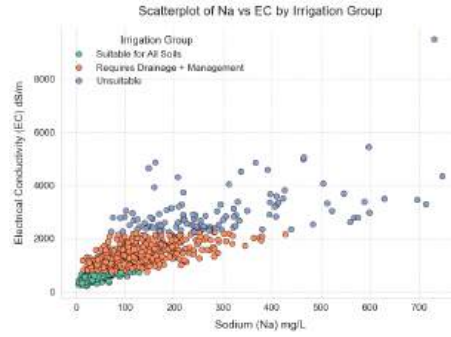


Figure 7: Scatterplot of sodium present versus EC, color coded by irrigation group.

Figure 8 shows the scatterplot of TDS and RSC, color coded by irrigation groups. The scatterplot indicates a negative correlation between TDS and RSC that fans out. Additionally, the scatterplot demonstrates a relationship with irrigation groups. “Suitable for All Soils” has little variety and is clustered with RSC values of around 0 meq/L, and TDS between 250 and 750 mg/L. Samples belonging to “Requires Drainage + Management” start to fan out, with RSC reaching 10 meq/L in both the positive and negative direction, and TDS of around 500 to just over 1000 mg/L. “Unsuitable” samples fan out the most at the end with RSC values as high as 20 meq/L and as low as negative 30 meq/L, and TDS between 1500 and 3500 mg/L.

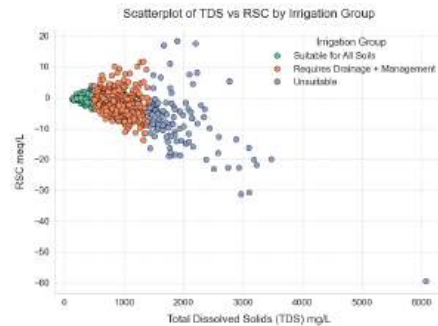


Figure 8: Scatterplot of TDS versus RSC, color coded by irrigation group.

Methodology

Data Pre-Processing

Due to severe data imbalance, the first step in data pre-processing is to group the data as shown in Figure 2. The nine quality classes (Figure 1) vary but can be grouped under the following: “Suitable for All Soils”, “Requires Drainage + Management”, and “Unsuitable”. C1S1 and C2S1 have low to medium salinity and low to medium sodium so they are classified as “Suitable for All Soils”. Classes C3S1, C3S2, and C3S3 have high salinity and low to high sodium and therefore are classified to the “Requires Drainage + Management” group. The remaining classes, C4S1, C4S2, C4S3, and C4S4, have very high salinity and low to very high sodium, and are considered “Unsuitable”.

We removed certain categorical variables: the district, mandal, village, and season (given that they were all post-monsoon) along with latitude and longitude. Due to the presence of high collinearity as shown in Figure 3, we dropped the following features - chloride, sodium, TDS, EC, and TH. In terms of physical properties, as the classification is based on salinity and sodium amount, to avoid data leakage, sodium and chloride are dropped as well. TDS directly contributes to salinity, and based on our correlation matrix, we know that it is perfectly correlated with EC. Lastly TH measures calcium and magnesium which continues to salinity and as it is correlated with EC, TDS and chloride, it was also dropped.

Models and Evaluation Metrics

We investigated both an unsupervised and supervised approach to predict groundwater quality. For the unsupervised approach, we were interested in understanding how our model would group together our data based on its physical and chemical properties. We were curious to see how the groupings would align with those already given to us by experts or whether we would create a new classification. For supervised learning, our objective was to create accurate predictions that followed existing classifications.

Unsupervised Learning Approach

Unsupervised learning is where the machine receives input features, but the target outputs are unknown. Its goal is to cluster data into different groups based on our inputs through evaluating and finding patterns within the data (14). Our objective specifically is to see how unsupervised learning creates different groupings of water quality by drawing upon the physical and chemical factors that serve as inputs. Ultimately, we did not provide a target column.

There are several different unsupervised learning clustering algorithms. The objective of clustering is to divide the data into clusters in which the data within one cluster is similar or has similar properties to another (15). KMeans was the first clustering algorithm we implemented. KMeans splits the data into a specified number of clusters, k (15). Initially, centroids are chosen randomly and each data point is assigned to its nearest centroid. As centroids shift to the middle of clusters, the data points are reassigned. This process continues until the data points and centroids stop shifting, and clustering is complete (15).

The next model we implemented was GMM. GMM assumes all the data points come from a mixture of finite number of Gaussian distributions that is multimodal (16). GMM introduces a probabilistic approach rather than assigning to its nearest centroid like KMeans, by creating probabilities of likelihood that a data point belongs to a certain cluster. This relies on the Expectation Maximization (EM). Expectation is the expected value of the log-likelihood function given the current parameter exists, and Maximization updates the parameter to maximize that - essentially recalculating the covariance. The model is then parameterized by the mixture component weights, and the component mean and its covariances (16).

The final model we implemented was Spectral Clustering. Spectral Clustering groups data that is similar into clusters by modeling data as input similarity matrices, comparing how similar

each data point is to another (17). It performs eigen-decomposition to break apart the most similar patterns which are then used to cluster the data. There are many other unsupervised models, however, we specifically chose the ones which have the input parameter as the number of clusters, so we don't have to tune other parameters to identify the clusters.

The essential parameter of above mentioned clustering models is number of clusters. To find the optimal number of clusters, we employed the Elbow method. The Elbow method is based on the assumption that the ideal number of clusters produces small inertia - total intra-cluster variation (18). We ran the elbow method algorithm several times as a function of different number of clusters, between one and eleven. When graphed, the elbow of the graph is where the inertia drops, and therefore the corresponding number of clusters is optimal.

To qualitatively compare the clustering of these models with our true labels we utilized t-distributed stochastic neighbor embedding (t-SNE) for visualizations. t-SNE calculates a similarity score for each data point and then arranges those points in a graph so the neighborhood looks similar (19). We compared t-SNE graphs colored by true labels and the predicted labels (clusters) given by the various models to qualitatively understand the difference.

Supervised Learning Approach

Models

In supervised learning, the target output is known, and is the three grouped classifications - “Suitable for All Soils”, “Requires Drainage + Management”, and “Unsuitable”. Our objective with this approach is to find a model that can have high evaluation metrics and accurately predict the true quality of our water samples.

To begin, our data was split into train and test data using a stratified approach. Stratification is critical as it ensures that the ratio of classification remains the same in both the train and test data (20). Essentially, even though only 20% of the data is going to test, that 20% will have the sample ratio of classification groups as the remaining 80% of training data. The training data is what the model learns from, and the test data demonstrates the true performance of that model.

We implemented various models, starting with baseline logistic regression. Logistic regression predicts the probability that an input belongs to a certain group (21). This probability is found using the sigmoid function. The input to the sigmoid function is a combination of all the input features and their weights, and then the function maps an output number between 0 and 1 (22).

Next, we tested a K-Nearest Neighbors model, or KNN. KNN classifies inputs based on their similarity to other samples in a given class (23). The parameter k decides the number of neighbors, meaning that when attempting to classify a data point, it will look at the k closest points, and predict the class most similar between those points (23).

We also implemented a Random Forest model. Random Forest creates a group of independent trees based on randomization and combines their predictions to make a decision (24).

To construct each tree, both a random number of rows (samples) and columns (features) are chosen (24). After the trees are built, an input is fed through and the majority classification marks the final decision.

The final model we implemented is Extreme Gradient Boosting (XGBoost). XGBoost, similar to Random Forest, creates individual trees (25). It is an ensemble method that combines outputs from individual trees. However, the trees differ from Random Forest as boosting combines weak learners sequentially to ensure that each new tree corrects the error of the previous one. The weakness of trees is evaluated using a loss function, which is based on whether the true label and prediction agree (25). Therefore, the trees that follow all aim to reduce the loss.

Hyperparameter Tuning

After we established our baseline models, we conducted a hyperparameter tuning to improve each of them. This is done by adjusting certain parameters of the models until the evaluation metric of our choice is maximized using grid search method (26). To enhance the typical grid search method, we performed a repeated 3-fold stratified cross validation 10 times and had the reported evaluation metric be weighted f1 score.

We began with our XGBoost model. To do so, we chose to change the following parameters: `learning_rate`, `n_estimators`, `subsample`, `colsample_bytree`, `alpha`, and `lambda` as shown in Table 2. `Learning_rate` controls the step size that the optimizer makes updates to the weights. `N_estimators` is the number of trees in the model. `Subsample` is the fraction of observations used for each tree. `Colsample_bytree` is the fraction of features used for each tree. Lastly, `alpha` is the L1 regularization term on weights while `lambda` is the L2 regularization term. `Learning_rate` was tested at 0.001, 0.01, 0.1, 0.2, 0.3; `n_estimators` at 50, 100, 200; both `subsample` `colsample_bytree` from 0.6 to 1.0 with 0.1 increment increase; and both `alpha` and `lambda` from 0.001 to 100, multiplying by ten each time.

To hyperparameter tune our Random Forest model, we varied the parameters as follows: `n_estimators` tested at 100 to 500 with increments of 100; `max_features` from at 'sqrt' and 1 to 12 with increases by 1; `min_samples_split` tested at 2, 5 and from 20 to 100 with an increase of increments by 10; 'max_depth' was tested at 3 to 15; and 'min_samples_leaf' was tested from 1 to 7. `Max_features` is the number of features to consider when splitting a node and `min_samples_split` is the minimum number of samples required to split an internal node. `Max_depth` is the maximum depth of each decision tree and `min_samples_leaf` sets the minimum number of samples that must be present in a leaf node. We also modified the `class_weight` by setting it to `balanced_subsample` or `balanced`.

Table 2: Model parameters and their value ranges

Model	Parameter	Range
XGBoost	<code>learning_rate</code>	[0.001, 0.002, 0.005, 0.01, 0.02, 0.05, 0.1, 0.2, 0.3]
	<code>n_estimators</code>	[50, 100, 200]

	subsample	Between 0.6 and 1 with increment of 0.1
	colsample_bytree	Between 0.6 and 1 with increment of 0.1
	alpha	[0.001,0.01, 0.1, 10 100]
	lambda	[0.001,0.01, 0.1, 10 100]
Random Forest	n_estimator	Between 100 and 500 with increment of 100
	max_features	Between 1 and 12 with increment of 1
	min_samples_split	Between 5 and 100 with increment of 10
	max_depth	None, between 3 and 15 with increment of 1
	min_samples_leaf	Between 1 and 10 with increment of 1
	class_weight	“balanced”, “balance_subsample”

Evaluation Metrics

To evaluate our models, we used various evaluation metrics. Precision is the proportion of positive cases that were correctly identified as positive. Recall is the proportion of actual positive cases that were correctly identified. Lastly, f1 score is the harmonic mean of both precision and recall. We particularly focused on this metric because it takes into account both false positives and negatives, and is useful when looking at an imbalanced data set. When comparing the train and test data, we strived to reduce overfitting - essentially when the model just memorizes the data - by tuning the models.

However, evaluating the test score only gives us one number for the particular test set we are using. To account for uncertainty, we calculated confidence intervals for test data metrics using our best tuned model and the bootstrap method. The bootstrap method draws repeated samples of test data thousands of times with replacement to stimulate what a new test set would look like (26). As it's done 1000 times, for each bootstrapped data sample the evaluation metrics - precision, recall, and f1 score for each label are all calculated. Using those values a confidence interval is created, telling us how the metrics for our test results can vary based on the sample we select.

Additionally, we calculated confidence intervals for our cross validation metrics. Since the repeated (10 times) stratified 3-fold cross validation approach we utilized for our hyperparameter tuning already split the data for us, there is no need to implement the bootstrap method. For each fold from the cross validation, the best model is fit, trained, and makes predictions based on the new numerical labels. During this, the precision, recall, and f1 scores of each prediction are calculated. As this is done for each of the 30 folds, at the end, the mean and confidence interval for each metric taking into consideration each fold is computed. Ultimately, this interval tells us how the evaluation metrics can vary based on the different samples of data we test.

Feature Importance Analysis

Once we have built our best model, we aim to understand and quantify the contribution of our inputs on its predictions. Knowing which input impacted the target output the most, whether it was something expected like bicarbonate, or maybe unexpected such as potassium, it is beneficial to understand what affects water quality and how it does that. To do so, we will be utilizing Shapley Additive explanations (SHAP) values.

SHAP works with a game theoretic approach, measuring each player's contribution to the outcome (27). Essentially, each feature is assigned a value that represents its contribution, with positive values positively impacting the prediction, negative values negatively impacting the prediction, and the magnitude a measure of how strong its effect is. These values can be applied to a variety of machine learning models.

Results and Discussion

In this section, we are going to present the results of our models, starting with the unsupervised learning approach and then followed with the supervised learning approach. To evaluate our unsupervised models, we will qualitatively compare them with t-SNE visualizations. On the other hand, the supervised models will be compared quantitatively with different evaluation metrics. We will also present our findings from SHAP analysis.

Supervised Learning Results

As shown in Table 3, we have strong results with both the simple Logistic Regression and KNN model. Logistic Regression has the highest f1 train score of 90% for label 2, “Requires Drainage + Management” and a notably low margin of error for the test data of around 3.4%. Its f1 score is lowest for label 1, “Unsuitable”, due to the low recall. Overall the model shows a strong performance but is slightly underfitting. On the other hand, KNN indicates no evidence of over-fitting, with very small differences between train and test f1 scores for all three labels. Like Logistic Regression, it does best with label 2, with a train f1 score of 91%. However, label 1, “Unsuitable” has a low train f1 score of 68%, due to a low recall of 53%. Ultimately, the model is strong in reducing overfitting but has a low performance.

Table 3: Evaluation metrics of the baseline logistic regression and KNN models. Label 1 is “Unsuitable”, label 2 is “Requires Drainage + Management”, label 3 is “Suitable for All Soils”.

Model	Train/Test	Label	Precision	Recall	F1	Samples
Logistic Regression	Train	1	84	78	81	93
		2	89	91	90	480
		3	83	81	82	172
	Test	1	83.0 ± 14.6	82.4 ± 15.5	82.4 ± 12.0	23
		2	94.1 ± 4.1	90.9 ± 5.0	92.4 ± 3.4	121

		3	85.4 ± 9.7	93.1 ± 8.0	89.0 ± 6.5	43
KNN	Train	1	96	53	68	81
		2	88	95	91	421
		3	88	88	88	150
	Test	1	95.1 ± 8.3	55.0 ± 16.4	69.3 ± 14.2	35
		2	87.4 ± 4.5	92.8 ± 3.7	90.0 ± 3.2	180
		3	82.4 ± 8.4	87.7 ± 8.3	84.9 ± 6.5	65

As shown in Table 4, XGBoost’s best parameters are: alpha as 0.001, colsample_bytree as 0.6, lambda as 1, learning_rate as 0.2, n_estimators as 200, and subsample as 0.8. The model is slightly underfitting - for example, for label 1, “Unsuitable”, the train f1 score is 82%, and for test is 89%, with a large margin of error. Similar to our baseline models, XGBoost performed best for label 2, with a high test f1 score of 96.8%, and a small margin of error. Random forest - whose best parameters were max_depth as 10, max_features as sqrt, min_samples_leaf as 5, min_samples_split as 2, n_estimators as 200, and class_weight as “balanced” has excellent performance with no under or overfitting. For all three labels, the difference between train and test f1 score is less than 2%. Once again, its most accurate predictions were for label 2 (“Requires Special Drainage Management”), where the train f1 score was 92.3%.

Table 4: Evaluation metrics with confidence intervals of the tuned random forest and XGBoost models. Label 1 is “Unsuitable”, label 2 is “Requires Drainage + Management”, label 3 is “Suitable for All Soils”.

Model	Train/ Test	Label	Precision	Recall	F1	Samples
XGBoost 'alpha': 0.001 'colsample_bytree': 0.6 'lambda': 1 'learning_rate': 0.2 'n_estimators': 200 'subsample': 0.8	Train	1	89.4 ± 2.3	78.0 ± 3.3	82.9 ± 2.0	93
		2	91.5 ± 0.6	95.8 ± 0.6	93.6 ± 0.3	480
		3	93.1 ± 1.2	86.8 ± 1.2	89.8 ± 0.8	172
	Test	1	89.3 ± 10.7	89.15 ± 10.85	89.65 ± 8.55	23
		2	96.25 ± 2.95	97.15 ± 2.85	96.8 ± 2.1	121
		3	95.95 ± 4.05	93.95 ± 6.05	95.9 ± 4.1	43
Random Forest 'max_depth': 10 'max_features': 3 'min_samples_leaf': 5 'min_samples_split': 2	Train	1	83.1 ± 2.2	78.1 ± 3.4	80.3 ± 2.5	81
		2	91.6 ± 0.9	93.0 ± 0.7	92.3 ± 0.6	421

'n_estimators': 200 'class_weight': "balanced"		3	89.0 $\pm$ 1.6	87.6 $\pm$ 1.9	88.2 $\pm$ 1.4	150
	Test	1	79.35 $\pm$ 12.65	79.1 $\pm$ 13.2	78.6 $\pm$ 10.6	35
		2	92.25 $\pm$ 3.85	90.5 $\pm$ 4.1	91.4 $\pm$ 3.0	180
		3	84.6 $\pm$ 8.3	90.55 $\pm$ 6.35	87.45 $\pm$ 5.75	65

Our best supervised model from the 4 above is Random Forest. While the difference between Random Forest and XGBoost is marginal, Random Forest's performance is significantly better compared with baseline models, such as Logistic Regression. Random Forest does not over or underfit and has high evaluation metrics, specifically for label 2.

SHAP analysis results

Figure 9 shows the SHAP values for the features that predict the "Unsuitable" samples. When it comes to predicting "Unsuitable" samples, SAR, HCO₃, and Mg, have the most impact. Specifically, low values of SAR decrease the probability a sample will be classified as "Unsuitable" while high values of SAR increase that probability. The same is true for both HCO₃ and Mg. Interestingly, RSC has the opposite effect - low values increase the probability a sample is classified as "Unsuitable" and high values decrease that probability. Features such as F and CO₃ have little impact on an "Unsuitable" classification.

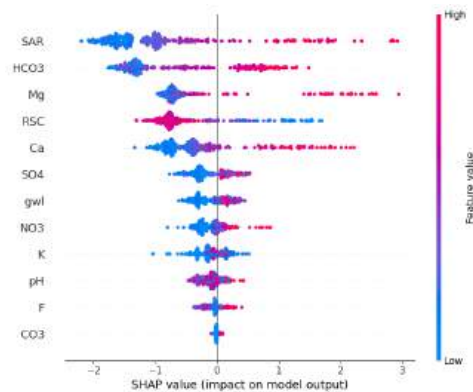


Figure 9: SHAP beeswarm plot for "Unsuitable" samples.

Figure 10 shows the SHAP values for the features that predict the "Requires Drainage + Management" samples. When it comes to predicting "Requires Drainage + Management" samples, SO₄, HCO₃, and Mg, have the most impact. High SO₄ values decrease the probability of such classification, while low values increase that probability. For HCO₃ and Mg the opposite is true, as high values increase probability and low values decrease. Similar to "Unsuitable" samples, features such as CO₃, F, and pH have a little impact on classification, and overall, features tend to have lower SHAP values, with most being between -1.5 and 1.5.

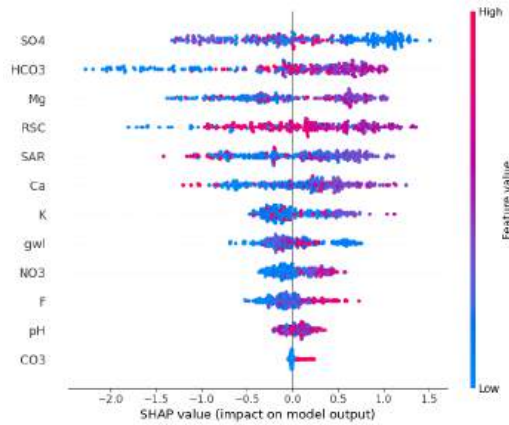


Figure 10: SHAP beeswarm plot for “Requires Drainage + Management” samples.

Figure 11 shows the SHAP values for the features that predict the “Suitable for All Soils” samples. When it comes to predicting “Suitable for All Soils” samples, similar to “Unsuitable” samples, HCO₃, Mg, and SAR have the most impact. High values of all three of those features increase the probability a sample will be classified as “Suitable for All Soils” and low values decrease it. This is true for most features except RSC and pH. Additionally, pH, F, gwl, and CO₃ have much less of an impact on the classification of these samples.

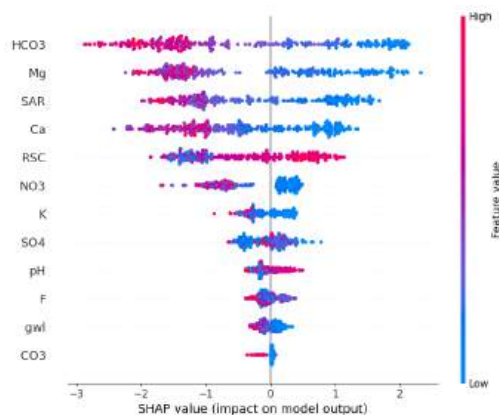


Figure 11: SHAP beeswarm plot for “Suitable for All Soils” samples.

Figure 12 shows the SHAP summary bar plot for “Unsuitable”, “Requires Drainage + Management”, and “Suitable for All Soils”. As seen in Figures 13, 14, and 15, the features that contributed most to classifications are Mg, HCO₃, and SAR. For Mg and HCO₃, these features contributed most for the “Suitable for All Soils” classification. For SAR, the contribution is roughly equal for “Unsuitable” and “Suitable for All Soils”. Similarly, for most remaining features, the contribution is least for “Requires Drainage + Management” with the expectation of SO₄.

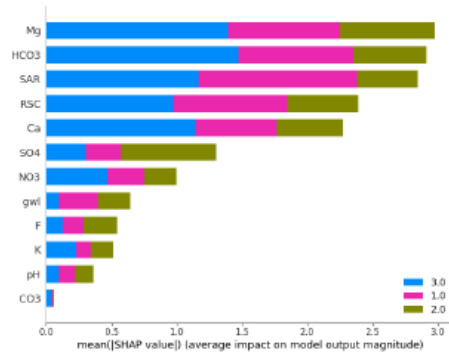


Figure 12: SHAP summary bar plot for all irrigation groups.

Unsupervised Learning Approach

We trained KMeans, GMM, and Spectral Clustering algorithms, but first had to find the optimal number of clusters. With the KMeans algorithm, we utilized the Elbow Method.

Figure 13 illustrates the elbow method for optimal clusters using KMeans algorithm. It shows the relationship between the tested number of clusters and intra-cluster variation. As seen in the graph, the elbow (or biggest drop in intra-cluster variation) is between two and four clusters, indicating that is the optimal amount to utilize.

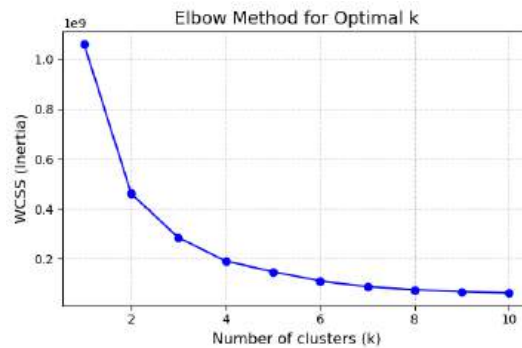


Figure 13: Elbow method graph for optimal clusters using KMeans.

Figure 14 shows the t-SNE visualization colored by true labels of our dataset and predicted clusters using KMeans algorithm with two scatterports. From the scatterplot on the left, we can see that KMeans predicted “Unsuitable” samples similar to what they truly are with the boundary just being slightly more to the right than the true labels. However, the boundary between “Requires Drainage + Management” and “Suitable for All Soils” is much farther to the right when predicted by the KMeans algorithm - meaning there was much more samples predicted to be “Suitable for All Soils” when they actually belong to “Requires Drainage + Management”. However, as a qualitative comparison, it is critical to remember that our unsupervised learning models do not predict our exact labels, they just predict clusters.

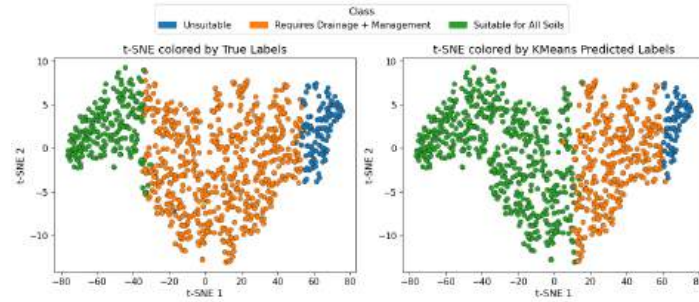


Figure 14: t-SNE scatterplots for true labels and predicted clusters by KMeans model.

Figure 15 illustrates the t-SNE visualization for the true labels of our dataset and the predicted ones by the GMM algorithm with two scatterplots. The “Unsuitable” samples were predicted by GMM in a similar pattern towards the right of the graph. However, GMM predicted “Requires Drainage + Management” samples with no clear boundary that stretch across the entire graph and are the majority of data points. Furthermore, the GMM model predicted very few “Suitable for All Soils” samples, with only around 10 or 20 data points. In comparison with the true labels, the boundaries between each cluster predicted by the GMM model are not consistent.

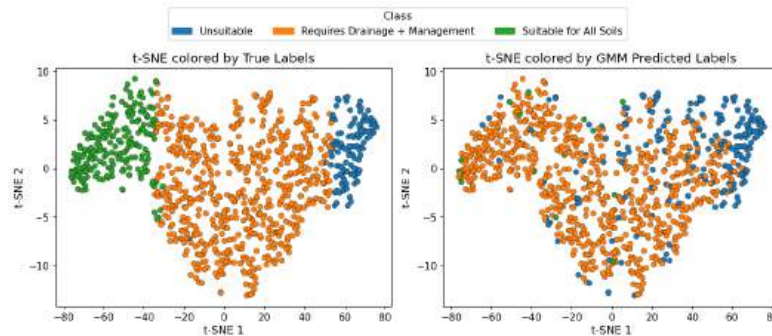


Figure 15: t-SNE scatterplots for true labels and predicted labels by GMM model.

Figure 16 shows the scatterplot with t-SNE visualizations for the true labels and predicted labels by the Spectral Clustering model with two scatterplots. The “Suitable for All Soils” and “Requires Drainage + Management” clusters are predicted with very consistent boundaries in comparison to the true labels. The boundary between “Requires Drainage + Management” and “Unsuitable” is predicted slightly more to the left than the true labels, but the two scatterplots demonstrate overall consistency.

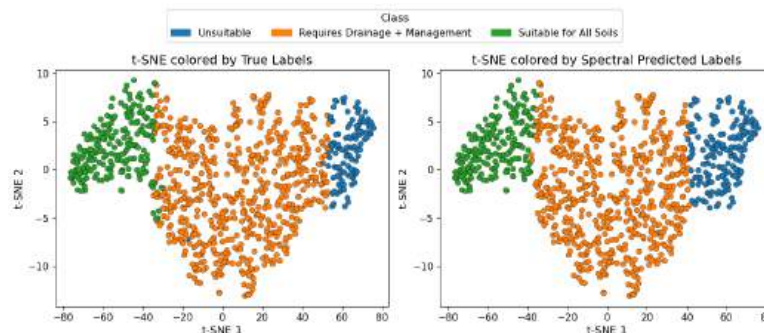


Figure 16: t-SNE scatterplots for true labels and predicted labels by Spectral Clustering model.

Based on Figure 14, Figure 15, and Figure 16, our best model is Spectral Clustering. The qualitative t-SNE visualizations show that its predicted labels for the three clusters of water quality groups match very closely when compared with the true labels, and best out of the three unsupervised models we implemented.

Discussion

We utilized both supervised and unsupervised learning approaches to make water quality predictions. Our supervised approach revealed our best model to be a hyperparameter tuned Random Forest, only marginally better than a tuned XGBoost, but significantly stronger than our baseline models. It had test f1 scores of 91% and 87% for labels 2 and 3, respectively. Its predictions, along with the predictions from all our supervised learning models, tended to be slightly weaker for our label 1, "Unsuitable" - likely due to few samples in that classification. The benefits of this supervised approach are that they are more easily evaluable with clear metrics and they tend to have high accuracies. However, issues can arise with overfitting and underfitting, along with label imbalance.

On the other hand, our best unsupervised model was Spectral Clustering. We were solely able to compare this quality with a t-SNE visualization, but its cluster predictions were consistent with our true labels. Unsupervised learning can find hidden patterns within our data set and it is beneficial as we can adjust the clusters as we see fit. However, they are more difficult to evaluate with no quantitative metrics.

Our results compared to previous works have similarly high results, however they are notable for various reasons. With hyperparameter tuning we were able to increase recall and f1 scores and reduce overfitting. We also included a vast variety of features as our inputs. We removed only five compared to about ten from previous works, which is beneficial as the predictions are not only more accurate, but are able to be made from a diverse set of inputs (12).

With SHAP analysis, we found that Mg, HCO₃, and SAR are the features that impact quality classification the most - among all classes. Furthermore, SO₄ has an impact in specifically the "Requires Drainage + Management" classification. A feature like SAR is expected, as our classifications were based on sodium and how well it could be absorbed. Mg contributes to hardness and could cause potential soil dispersion. HCO₃ also increases sodium hazard. SO₄ is less expected, but ultimately also contributes to salinity and elevated levels can cause health problems (9). From our SHAP summary bar plot, we also found out that features impact classes "Unsuitable" and "Suitable for All Soils" more than "Requires Drainage + Management". As "Requires Drainage + Management" was a broad class and ranged from water that needs minimal drainage to water that requires soil permeability and special management, it is understandable that it has a weaker feature impact due to more diversity within its belonging samples.

Our study looked specifically at the Telangana region of India that relies heavily on irrigation. Our dataset had a very unbalanced classification to begin with, so we grouped the data. This grouping improved the imbalance, however it made generalizations on the suitability of

water. For example C4S1 quality water could be used for irrigation if the soil is permeable and there is adequate drainage, but for grouping purposes, it was classified as "Unsuitable". Our dataset was also slightly limited in the fact that it only had data in the post monsoon season and was limited to just Telangana state, which is an arid region, meaning our results may not apply to differing climates. Therefore, it would be beneficial to test our models in other regions.

We used grouping techniques, as well class_weight balancing methods to handle the data imbalance. However, there are other techniques such as oversampling (SMOTE) to create a synthetic dataset to balance out our data. Employing such techniques further would be very beneficial for future work.

Conclusions

Ultimately, our objectives were to accurately predict quality for agriculture purposes and discover what features were most impactful. We aimed to do this through a supervised and unsupervised approach, inputting features that did not directly classify the particular quality we were looking at - namely salinity and sodium. We wanted to be as accurate as possible and simultaneously reduce overfitting to ensure our models truly understood patterns within our dataset.

We employed both an unsupervised and supervised approach, testing a variety of different algorithms. We created confidence intervals to account for uncertainty in our evaluation metrics and hyperparameter tuned models to reach peak performance. For the unsupervised learning models, we utilized the Elbow method to find the optimal number of clusters. With these approaches, our best unsupervised model was Spectral Clustering and our best supervised model was Random Forest. The Random Forest model had test f1 scores of 0.87 and 0.91, along with very low margins of errors for labels 2 and 3.

Our SHAP analysis identified features of HCO_3 , Mg, and SAR to contribute most to the classification of water quality. Aside from the "Suitable for All Soils" class, it was high values of HCO_3 that corresponded with a high probability to be classified in the given class. High values of these features increased the probability that a sample would be classified as "Unsuitable" and low values indicated it was likely to be classified as "Suitable for All Soils". In general, there was a pattern of a higher value corresponding to a higher probability of a sample being classified as "Unsuitable" aside from RSC - where the opposite occurred. The impact of features was weakest for our most diverse and broad class of "Requires Drainage + Management", where the feature with most impact was SO_4 .

Future work with an unsupervised approach could continue to increase the accuracy of predictions for water deemed unsuitable for irrigation, while also reducing overfitting. On the supervised approach, similarly, more tuning can strive for more accuracy - maybe through more data on the Telangana region, or similar semi-arid regions.

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Key Factors Affecting Children's Mental Health and Well-being in Rural Nepal

By Amara Obaray

Abstract

Understanding mental health and well-being in children in rural Nepal is crucial, as it enables a deeper comprehension of Nepal's cultural context. This literature review examines the key sociocultural factors influencing the mental health of school-aged children in rural areas of Nepal. Key factors include economic status and the community's role. The emphasis on mental health and promotion of interventions in Nepal continues to gain prominence, although this growth depends heavily on the country's overall development. Addressing and understanding these barriers to create more effective mental health interventions is critical to improving the mental health of children in rural Nepal. This research highlights that the existing literature on this topic often relies too heavily on self-reported data from parents, rather than children, which limits the applicability of certain conclusions. Moreover, this paper contributes to the existing scholarship on child mental health in Nepal by highlighting the interplay of economic, familial, and community-based dynamics in shaping the well-being of Nepali children. In summary, this paper's intervention is to synthesize fragmented research findings into a consolidated culturally specific framework for understanding the issue of child mental health in rural Nepal.

Introduction and Author's Note

In the summer of 2024, I had the opportunity to immerse myself in the rural areas of Nepal, living with and attending schools run by an organization that supports girls and children who are orphaned or trafficked, providing resources and care to underprivileged and orphaned children. My perspective on both Nepal and the world changed as I became aware of the drastic cultural differences that I had previously been accustomed to. The job entailed considerable physical and pedagogical work, including developing the dorm itself and tutoring children in English in the afternoons. I also spent time at the Arhaus Children's Home, where I introduced the children to American games and lesson plans. The organization, This Small World, aims to empower underserved communities in rural Nepal by providing healthcare, education, and sustainable development initiatives. As a group, it focuses on creating actionable and sustainable paths to provide necessary resources to local communities. As I spent time with these kids, I began to see their dispositions. Despite their situations, they undoubtedly illuminated happiness and resilience. This observation posed a question of how Nepal as a whole deals with mental health issues, particularly regarding underprivileged kids. I wondered if circumstances like poverty and lack of resources had an impact on the children's well-being and mental state while overcoming those challenges, and if so, what common socio-cultural factors played a role in that?

My initial curiosity stemmed from the idea that economic status and its hierarchy can cause a tendency to create superiority and competitiveness within a community. Arguably, the community may then become divided and less "communal," which therefore may cause a person's mental health to worsen as they are not benefiting from social engagement and collectivism. Instead, they could experience extreme independence and loneliness. When people

have a lower economic status, are they more open to collaborating because they are in a more vulnerable state? Does community engagement and support, ensuring that one can rely on their community, improve a child's mental health? In my own experience, being able to rely on other people helps the feeling of being alone and improves the ability to overcome challenges; if people are not in a community where they can rely on community members, then their mental health may deteriorate.

This research will explore several questions, such as: to what extent does community support influence the mental health of school-aged children from low-income families in rural Nepal? Can certain interventions play a role in alleviating the disadvantages of economic disparity? This paper examines a range of research studies, from family dynamics (Ma 2022; Adhikari 2025; Pacini 2024; Rana 2025) and parental well-being (Ma 2022; Adhikari 2025; Rana 2025) to behavioral problems (Ma 2022; Adhikari 2025; Burkey 2016; Rana 2025), economic inequality (Ma 2022; Adhikari 2025; Loksam 2021; Rana 2025), and culturally adaptive interventions ((Ma 2022; Adhikari 2025; Pacini 2024; Burkey 2016; Rana 2025).

Methods

This literature review compiles information from various sources on factors that impact the mental health and well-being of school-aged children in rural Nepal. Google Scholar was used to identify sources, and six sources were selected for this literature review. The sources shared common themes and typically fell within the disciplines of public health, education, and psychology. Based on the research reviewed for this study, the discussion will focus on three major themes and their impact on the mental health and well-being of children in Nepal.

Discussion

For centuries before the development of modern psychiatry in the West, many Nepalis, as with other South Asian communities, drew on traditional healing practices – one of the cultural factors that has made it difficult to engage rural populations today. The first psychiatric outpatient department was established in 1961, following Nepal's independence. Although the country began to emphasize mental health in the early 2000s, most of this development has occurred in urban, rather than rural, communities.

Within existing research, several key socio-cultural factors have been identified. The most common themes identified were references to family dynamics/ social upbringings, community engagement, and ideas supporting economic status and community support for Nepali people. The impact on mental health due to these factors was demonstrated. Other socio-cultural factors identified included physical and social settings (environment/culture), as well as employment opportunities and economic and social indicators/upbringings.

Economic Factors

Disparities in economic status impact children's mental wellness in rural Nepal. Factors such as parent and child levels of education, accessibility to health resources, and societal acceptance of different background groups contribute to mental health outcomes.

One study found that specific groups of people experience disadvantages in accessibility to mental health resources. Several variables, including geography, caste, and gender, significantly predict income, consumption levels, inclusion policies, access to resources, and participation in governance (Loksam, 2021). Because these groups experience such disparities, children within these communities typically face higher risks of emotional and behavioral problems. Access to mental health resources and guidance is limited, as well as knowledge and understanding of the impact of mental health disorders. Another study supported this finding by relaying that many children from a particular group often suffer from mental health illnesses or abnormal behaviors due to social rejection and long-term societal marginalization (Adhikari, 2015). For families of low-income, lower education, and certain castes, the social divide creates a sense of isolation, causing children within these communities to have increased mental health disorders. This sense of isolation can cause them to perform poorly academically, exhibit negative social behaviors and aggression, and experience emotional distress (Adhikari, 2015). These behaviors hinder their ability to interact with Nepali society as adults due to weakened social skills and a disrupted thought process. The Nepali government has taken limited measures to intervene in this public health crisis, though this approach does not alleviate longer-term mental health ailments. This could lead to a decline in overall mental health, as parents with mental health disorders could parent their children when they are ill-equipped and without ever receiving proper support. Social interventions should be delivered early on in a child's life if they show signs of atypical behaviors or emotions.

A third study found that higher parental education was unexpectedly associated with more mental health problems among children, possibly reflecting the under-reporting of problems by illiterate or minority parents (Ma, 2022). Underreporting by the illiterate or minority parents could pose challenges by biasing data points when deciding what will be the most constructive and beneficial potential interventions for the majority. This finding challenges traditional assumptions that educated parents will be more likely to understand the impact mental health disorders can have. Instead, this finding is possibly due to the cultural norms and values in Nepal, suggesting that educated parents may only identify mental health disorders as what Nepal culturally believes in. This provides further insight into the lack of knowledge and accessibility marginalized groups have to mental health and treatment resources.

Additionally, a fourth source suggests that while cultural adaptation to new ways of thinking and new social practices is recognized and often applied, it largely remains superficial. The inclusion of the family and community consistently predicts better mental health outcomes, suggesting that culturally congruent system-level adaptations may be key to improving child and adolescent mental health in Nepal (Pacini, Broker, & Shrestha, 2024). This is especially important for children's well-being in Nepal because these factors help us understand the culture and the disparities within the country that have a significant effect on children's mental health. Together,

these studies illustrate the inequities within the country and the contributing factors for potential interventions.

Family Dynamics

While economic factors play a role, family dynamics are more prevalent when considering direct impacts on children's mental health and well-being. Family dynamics have the most direct impact on a child's mental wellness, making it the most significant factor correlated with mental health illnesses. Aspects of family dynamics include parental discipline, parenting quality, parental mental health, how parents perceive their child's behaviors, and family dysfunction. The most important of these aspects has more of an impact on the likelihood of a child having a mental health disorder.

One source found that inconsistent discipline by parents combined with increased parent-child conflict had significant effects on a child's well-being. This was related to children reporting higher emotional symptoms, including anxiety, anger, and low prosocial behavior. Furthermore, parenting quality accounted for 12-26% of the variation in children's emotional/behavioral outcomes. This report showed 22.4% of caregivers reported clinically significant levels of depression and anxiety, especially in mothers, those facing food insecurity, and those with lower perceived social standing. A lack of social support, socio-economic perceptions, and food insecurity in low-resource communities impact parental stress and mental well-being. Children's emotional and behavioral outcomes are impacted through decreased parental mental health, poor parenting quality/parenting practices, and parent-child conflict (Rana³, 2025). Another source found the key behavioral problems in children that were most commonly identified were: not paying attention to studies, addictive behaviors (alcohol, drugs), getting angry easily, disobedience, negative social behavior (fighting, aggression), emotional distress (anxiety, depression, isolation), social exclusion, and stigmatization. The perceived causes of these behaviors were: an unfavorable family environment (violence, neglect, substance abuse, mental health illnesses), poverty, too little parental attention, and lack of good school and community environments (Adhikari, 2015). A third study reiterates that children have higher mental health issues when more conflict between family members occurs, as well as greater behavioral problems when physical punishment is used frequently (Ma, 2022). While these findings reveal similar ideas, it is essential to note that all data was obtained from parental reports or self-reported perceptions. This raises the possibility of biases due to parental perceptions of acceptable behavior, as well as infrequent direct behavioral observations. Understanding how family dynamics are a primary contributor to children's well-being in Nepal is important because of the cultural contributions affecting the parental behaviors towards their children (e.g., lack of social support, social standing, accessibility to proper guidance and resources) and cultural norms of acceptable behavior influencing how parents believe mental health illnesses should be handled as well as its level of importance. Together, these studies describe a domino effect of issues starting from parental mental health, to the direct impact on children's mental health and wellbeing.

Cultural norms not only influence family dynamics and parental management of abnormal child behaviors, but also the methods used by outside resources.

Community support and behavioral interventions

Community support and behavioral interventions play a crucial role in shaping the mental health of school-aged children in rural Nepal.

One study found that there are several current strategies used to discipline or provide support depending on the severity of abnormal behavior or mental health disorders. Strategies include verbal communication (advising and counseling), teacher involvement, the use of physical punishment when verbal methods fail, and occasional school-family collaboration (Adhikari, 2015). While these methods may be effective temporarily, there is a risk that if teachers and family members of a child are not properly educated on mental health disorders and how to effectively provide useful guidance and resources, the children's mental health disorders will progress and possibly worsen over time. One source offers suggested interventions that would be more useful than current temporary interventions to the long-term experience of a child with mental health issues. For example, they proposed interventions such as mental health awareness programs for parents, teachers, and children, as well as the development of educational materials. They mentioned family-based support for at-risk children and community-wide interventions through media and group discussions (Adhikari, 2015). The study recommends multi-level community-based interventions as feasible and culturally acceptable solutions to improve a child's behavior and well-being (Adhikari, 2015). Another source supports this finding by stating that rural Nepal conceptualizes child behavior problems in terms of the extent to which children fulfill their assigned role in society, their engagement in higher-risk situations, and how their child's abnormal behaviors impact society's perception of the family (Burkey, 2016). The ideas stated in the past paragraph supports the idea that knowledge and value of mental health disorders is low and therefore exemplifies the importance of these educational systems and accessible resources to children. This is especially important for children's well-being in Nepal, as this research provides insight into the existing methods used, as well as an understanding of how valued mental health is in rural Nepal. Together, these studies show the current community involvement and methods to support children suffering from mental health issues, and in turn provide alternative approaches to improve children's well-being.

Conclusion/Summary

Children's well-being in rural Nepal is shaped not just by their economic status, but by the quality and type of relationships that surround them. It is essential to understand better the barriers that decrease school-aged children's mental health in rural Nepal. These barriers, all similarly caused by cultural foundations, significantly influence their way of life. Several common factors that impact children's mental health and well-being include economic factors, family dynamics, community support, and behavioral interventions. Some economic factors that impact children's mental health are levels of education given to parents and children, accessibility

to health resources, and societal acceptance. Some aspects of family dynamics that affect children's mental health are discipline, parenting quality, parental mental health, perceived child behaviors, and family dysfunction. The current community support and behavioral interventions, such as counseling, discipline, or physical punishment, often lack long-term effectiveness. As a result, long-term multi-level community-based interventions are necessary to improve school-aged children's mental health in Nepal significantly. The limited quality of existing studies and the inconsistent application of formal adaptation frameworks suggest a need for more rigorous interventions and evaluations. It is essential to acknowledge that leveraging Nepal's current collectivist cultural norms, through group-based delivery involving schools, families, and communities, can be beneficial in better understanding current ideologies and identifying areas for change (Pacini, Broker, Shrestha, 2024).

Subsequently, interventions that are feasible and culturally acceptable can be made. Moreover, creating more interventions that are available to a larger portion of the community will increase normalization of mental health issues and, in turn, influence how things like discipline are approached differently within families. The lack of proper interventions that truly remedy a child's mental health issues has caused generations of Nepali's to continue the cycle of ignoring mental health issues. Policymakers and Nepali leaders can do a systematic transformation by taking into account the effects cultural norms have on this disparity. Through education, inflation of mental health resources, and a shift in the importance of mental health to the Nepali communities, equitable mental health care can be achieved.

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The Impact of Project-Based Learning

A Scientific Perspective By Sara Delal Samanci

Introduction

Project-based learning (PBL) is a dynamic classroom approach in which students build their knowledge of a subject through experiential learning. Differing from the traditional lecture-based approach commonly used in American high schools, PBL's origins lie in 20th-century philosophical principles tracing back to John Dewey's "learning by doing" which his pupil William Kilpatrick later developed into the "project method." PBL aims to guide students to gain a deeper knowledge of real-world issues via active learning. Researcher and associate professor Hao Yu from the Division of Health Policy and Insurance Research at Harvard Medical School found that PBL has been increasing students' motivation and information capacity as well as enhancing cognitive engagement and dynamic thought. Despite PBL's relatively recent appearance, Aziz Sheikh-Abded, a PhD recipient and lecturer from the Israel Institute of Technology, notes that engineering colleges have used PBL actively in their curricula for over 20 years, showing its positive impact on cognitive abilities and behavior. Although PBL offers significant benefits in cognitive engagement and behavior, its effectiveness depends on its implementation and integration with traditional methods.

Elements of PBL

PBL is unlike any traditional classroom method, with its distinct curriculum and assessment systems. The curriculum is divided into four categories: setting the project theme, autonomous theme building, outcome optimization, and comprehensive summary and assessment. Setting the project theme facilitates the rest of the project and paves way for the entire learning process, shaping students' learning experiences, creativity, and integrated learning skills. After identifying an issue, students then conceptualize possible solutions. This step promotes creative reasoning and problem-solving skills by giving the experience of applying knowledge in realistic scenarios. Once students identify a feasible solution, they present their ideas, reflect on their acquired knowledge, and apply their critical thinking skills. Students are actively reassessing while presenting their research, emphasizing an understanding of a topic to lead to growth and development (Yu, 2024).

Metacognitive Ability

Metacognition refers to the capacity to comprehend one's cognitive abilities, encompassing both strengths and weaknesses in performing tasks (Sheikh-Abded 2023). Metacognitive assessments are a crucial part of the PBL curriculum as they compare students' perceived performance with their actual performance. Brandon Slade, CEO and founder of Untapped, an established international organization aimed at helping students develop their executive functions emphasizes that this type of assessment motivates students to put their executive function skills to use in projects. This in turn promotes a deeper understanding of the

material. Research conducted by Hava Vidergor, a senior lecturer of curriculum and instruction at the Gordon Academic College of Education and Arab Academic College, further emphasizes this by stating that students in PBL classrooms reported that they began to organize their thoughts more concisely thanks to PBL tools.

In contrast to Videgor and Slade, a study on students in an Israeli electronic high school showed that they scored 34.89 points higher on their self-report than what they received on the actual achievement test (Sheik-Abed). The data shows that although students think they are learning and comprehending material, they may be overestimating their abilities. Similarly, another study was done by scholars from Malaysian Universities; the International Islamic University of Malaysia and the School of Medical Sciences, Universiti Sains Malaysia. The researchers observed that 64% of the first-year students were unable to adapt to the PBL system because they had been accustomed to conventional learning settings and that 43% of students were not adequately prepared for the sessions and thus were minimally involved in the discussion (Shahreez Abdul Ghani et al. 2021). Because many of these students were introduced to PBL late in their academic paths, with little prior experience in similar environments, they often felt unprepared, leading to confusion and a false sense of knowledge acquisition.

Knowledge Acquisition

In a study done by CBS News, the average American only understands about 37% of what they learned in school, leaving a huge gap in forgotten knowledge. However, PBL students have demonstrated better knowledge acquisition than traditional classroom students. During the 2021-2022 school year, researchers divided 101 kindergarten students in Alanya, Turkey into two groups; one served as the control group. This study conducted by Yaren Nural, a PhD candidate at Alanya Alaaddin Keykubat University, Turkey, showed that the group that used project-based learning had a significant increase in team engagement, thought expression, and vocabulary compared to the control group. Building on these findings, a sister study done in England over a 3-year duration revealed that the experimental group received three times as many points on the combined central exam at the end (Nural, 2023). Together these two studies highlight PBL's support of long term knowledge retention, making it a valuable complement to traditional instruction.

Impact on Behavior

Teaching is one of the most stressful occupations, as evidenced by the National Institute of Health's study revealing that 87.1% of teachers reported a high amount of stress while at school. Additionally, another study done by PhD and MEd students at a school in Pennsylvania, states that teaching special education is even more stressful due to the high rate of immature and impulsive behavior reported, resulting in these teachers having a higher risk of burnout compared to general education teachers. To reduce teacher stress and improve student behavior, PBL was integrated into a special education class where students were observed for physical and verbal violence, poor interaction skills, and misbehavior. To measure behavioral change, teachers were

told to record misbehavior. According to their findings, “All students had a visible immediate effect of using PBL to improve behavior” as well as “both the teacher and the paraprofessional indicated increased job satisfaction from pre- to post-ratings” (Jonte’C et al. 2024). The data shows that PBL does affect both students and teachers, making it easier for teachers to attend to their students, which better supports special education students while minimizing teacher stress.

Conclusion

In theory, project-based learning is the perfect curriculum to help students better comprehend the material and be more prepared for their future careers. However, multiple sources demonstrate that the topic of PBL is complex and is neither definitively positive nor negative as a teaching method, just as traditional curricula have both advantages and disadvantages. For instance, students with special needs who have behavioral problems benefit from PBL, but PBL alone is not enough to improve all cognitive abilities. To improve student growth, PBL should not replace traditional teaching, but rather be integrated with it, creating a system that supports diverse learning needs and gives the opportunity for students to excel across multiple disciplines.

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How Population Models Have Been Modified to More Accurately Predict Real-World Population Dynamics By Sam Salser-Meyers

Introduction

Population modeling is one of the most explored topics at the intersection of the fields of mathematics and ecology. It refers to the mathematical study of how populations change over time - which often involves developing and testing equations and systems of equations that seek to predict real-world ecosystem dynamics by simplifying complex ecological interactions. These models are often derived from basic observations about predictable patterns and trends in population sizes in response to external biological or ecological factors. Population models vary widely in their assumptions, complexity, and accuracy, however they all serve the common purpose of representing specific ecological interactions among species.

A *population* is defined as a group of individuals of the same species that have a high probability of interacting with each other (“Density-Independent Population Growth”). Due to the intricate nature of real-world ecological systems, population models simplify these populations to allow for the creation of coherent mathematical representations. There are several ways to go about creating models predicting the dynamics of such populations. The two main types of equations are generally classified as either *continuous* or *discrete* (“Density-Independent Population Growth”). Continuous models account for population changes at every instant in time, thus producing a smooth curve when graphed. Discrete models, on the other hand, only account for population measurements at fixed time intervals. Discrete models are especially useful when graphing populations with fixed seasonal patterns of reproduction or those with distinct generations. Additionally, depending on the type of species or organism being modeled, difference equations, ordinary differential equations, delay differential equations, partial differential equations, or the combination of these equations may be used (Kuang). While almost all approaches are useful in unique ways, this paper will focus on the derivation and analysis of continuous ordinary differential equations (ODEs) due to their widespread usage and ease of application. They are also generally easier to adjust and modify in the pursuit of modeling specific ecological phenomena.

The development of simulations that predict such patterns is valuable due to their genuine usefulness in countless fields including but not limited to ecology, medicine, agriculture, mathematics, and even game theory (Huang et al.). For instance, they are crucial for ecological initiatives due to their ability to analyze real-world populations. Population models have also been used to predict the spread of diseases and pathogens including the recent COVID-19 pandemic, which could be crucial in their mitigation (Mahtani). These types of models have even been utilized to predict human growth dynamics, which has become more of a pressing issue in modern times (Kin et al.). While they certainly don’t achieve perfection, the models and modifications discussed in this paper have been integral to the development of more modern, accurate equations.

Methods

Most sources were obtained via Google Scholar to ensure accuracy and reliability. Graphs and solutions to ODEs were generated using Python's Matplotlib library. These visualizations display how varying parameters can affect population trajectories.

Single-Species Models

Understanding the art of mathematically modeling populations begins with a discussion of single-species models, which are the simplest due to their reliance on only one population and its intrinsic dynamics of growth. Single-celled organisms such as bacteria or yeast under laboratory conditions are often perfect for this type of model due to their predictable reproduction patterns and isolation from other species. In these species, each individual undergoes binary fission at each generation, effectively doubling population size.

The simplest way to describe single-species population growth is to assume that instantaneous population growth is directly proportional to population size. Mathematically, this can be expressed by the exponential growth model (Vandermeer):

$$\frac{dN}{dt} = rN \quad (1)$$

where N represents the number of individuals in the specified population, and r represents this population's intrinsic rate of natural increase. To predict population at any given time t , the exponential growth model can be integrated to derive the solution:

$$N(t) = N(0)e^{rt} \quad (2)$$

where $N(0)$ is the measure of the population at time $t = 0$.

The exponential growth model is especially useful for approximating early population growth at low densities, and its end behavior is entirely determined by the sign of r with just three cases to consider ("Density-Independent Population Growth"):

1. When r is greater than zero, the specified population N will increase indefinitely since $\frac{dN}{dt}$ would be positive.
2. When r is less than zero, the specified population N will approach zero since $\frac{dN}{dt}$ would be negative.
3. When r equals zero, the specified population N will not change since $\frac{dN}{dt}$ would also equal zero.

While exponential growth does a good job at modeling population growth at its early stages, its main flaw lies in the fact that it allows for indefinite growth. This is impossible in the real world for countless reasons. Actual organisms experience both biotic and abiotic limiting

factors that are capable of influencing organism survival and reproduction (Edwards and Edwards). Abiotic (nonliving) factors such as resource and shelter availability limit population by constraining the physical environment. For instance, high-density red squirrel populations are limited by habitat quality as a result of territoriality (Wauters et al.). Biotic (living) limiting factors such as intraspecific competition, predation, and disease also significantly affect population dynamics, although they are perpetrated by living organisms. Limiting factors are either classified as density-dependent or density-independent based on whether their impact scales with population size. For example, intraspecific competition would be considered density-dependent while natural disasters would not. It is these density-dependent limiting factors that ultimately result in a concept known as a population's carrying capacity, which refers to the maximum number of individuals that a given environment or ecosystem can sustain.

Assuming the rate at which a population is increasing at any given point in time is directly proportional to the difference between the population's carrying capacity and the population itself, the population can be modeled by the logistic growth model (Vandermeer):

$$\frac{dN}{dt} = rN\left(1 - \frac{N}{K}\right) \quad (3)$$

where K represents the population's carrying capacity. You will notice that this new equation is simply the exponential growth model (Equation 1) modified by adding a $\left(1 - \frac{N}{K}\right)$ term, which can be rewritten as $\left(\frac{K-N}{K}\right)$. This term approaches zero as the specified population N tends toward the carrying capacity K , leading to an eventual stabilization of the population near its carrying capacity. Note that for density-based models, the term $(1 - N)$ is often used instead of $\left(1 - \frac{N}{K}\right)$ assuming the carrying capacity of the given population is 1 (Diz-Pita and Otero-Espinar).

The logistic growth model certainly improves upon the exponential model by accounting for limiting factors on population size, however it is still limited by the fact that it does not consider the effects of one population on another, such as the impact of predators on prey and vice versa.

Classic Lotka-Volterra Model

Perhaps the most famous predator-prey model of mathematical ecology was independently developed by both Alfred Lotka and Vito Volterra in the 1920s as a way to explain cyclic behaviors and unexpected trends in observed populations of the time (Kingsland). Their work was among the first to produce these periodic oscillations, which was a crucial breakthrough in population modeling. Their model improved upon earlier ones by taking multiple populations into account, including important feedback effects that are present in the real world. The Lotka-Volterra system resulted in more accurate and meaningful predictions of population dynamics than single-species logistic and exponential models, however its simplicity also relied on many inaccurate and unrealistic assumptions which limited its applicability in real world ecosystems. Despite this, their model remains a fundamental part of theoretical population

dynamics, inspiring countless improvements and new models over the past century.

While their model assumes many different forms, the most widely studied and influential representation of their ideas is the system of equations (Mira-Cristiana):

$$\begin{aligned}\frac{dx}{dt} &= \alpha x - \beta xy \\ \frac{dy}{dt} &= \delta xy - \gamma y\end{aligned}\tag{4}$$

where x and y represent the predator and prey populations respectively, referring to either absolute population size or density depending on the context. α represents the inherent prey growth rate (named by Volterra as the *coefficient of auto-increase*). β represents the negative effect of predation on the prey population, while δ represents the positive effect of predation on the predator population. Finally, γ represents the inherent death rate of the predators.

The model makes three key assumptions about the environment and the populations being modeled (Adamu):

- The prey population has access to an unlimited supply of food, meaning it will grow indefinitely in the absence of predators.
- The rate of predator-prey interactions is directly proportional to the value of the product of the two populations.
- The predators depend on prey for survival, meaning the predator population will decline in the absence of prey.

These assumptions lead to several interesting system dynamics that reflect how predator and prey populations affect one another over time. For example, when the predator population y equals zero, the term βxy will also equal zero and therefore the growth rate of the prey population is able to grow independently at its intrinsic rate without being limited by predation. Similarly, when the prey population x falls to zero, the predator population growth rate will remain negative until the predator population reaches zero. This is due to the fact that the δxy term would equal zero, which makes sense since predators require prey to survive.

We can find the steady states of this system of equations - that is, when both predator and prey populations are not changing - by setting both $\frac{dx}{dt}$ and $\frac{dy}{dt}$ to equal zero. Solving for x and y yields two equilibrium points which are $x = 0, y = 0$ and $x = \frac{\gamma}{\delta}, y = \frac{\alpha}{\beta}$. Ecologically, this means that both the predator and prey populations are unchanging when both are extinct (which is trivial). More interestingly, it shows us that both predator and prey populations are constant when the prey population is equal to $\frac{\gamma}{\delta}$ and the predator population is equal to $\frac{\alpha}{\beta}$. Any starting populations different from these will result in periodic oscillations as is usually the case with the classic Lotka-Volterra System.

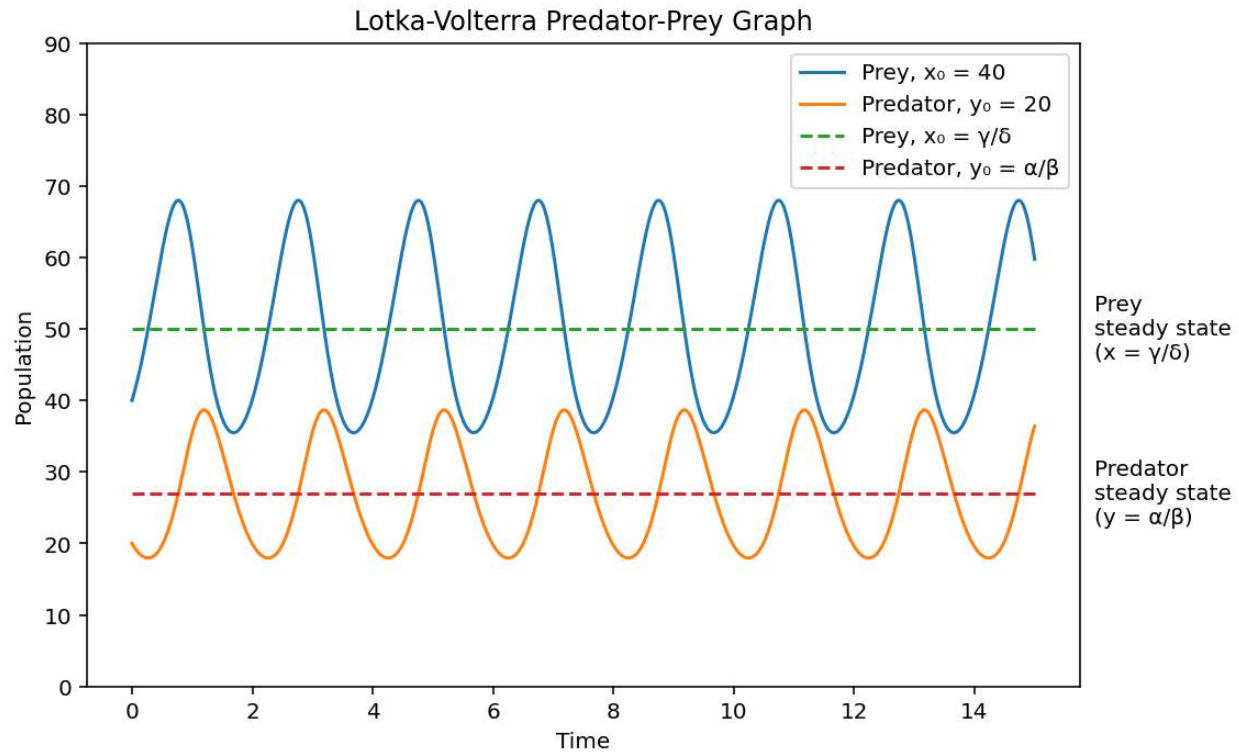


Figure 1: Lotka-Volterra System with $\alpha = 2.7$, $\beta = 0.1$, $\delta = 0.075$, and $\gamma = 3.75$.

Figure 1 displays the behavior of a Lotka-Volterra System for two sets of initial conditions, one resulting in periodic oscillations and the other resulting in a steady state. These oscillations are entirely determined by the initial values for predator and prey populations. You will also notice how peaks in predator population tend to appear following peaks in prey population, which is a phenomenon widely known as phase lag.

Further Modifications of the Population Models

While the Lotka-Volterra Model addresses numerous flaws and unrealistic assumptions of single-species models by introducing interspecific interactions, it still displays several limitations and inaccuracies that fail to capture many ecological dynamics of the real world. Luckily, many of the aforementioned flaws can quickly be fixed or improved by the introduction of simple modifications in the form of new constants and coefficients of existing terms in the dynamical system.

Logistic Growth

One of these flaws lies in the assumption that the prey population has access to an unlimited supply of food, resulting in unrestricted exponential growth in the absence of predators. Similar to how we improved the basic exponential growth model by introducing a term restricting

population through the concept of carrying capacity, we can introduce $(1 - \frac{x}{K})$ into the Lotka-Volterra System (Equation 4) by multiplying it with the prey growth term αx (logistic growth can also be introduced to the predator growth equation although this is less common) (Diz-Pita and Otero-Espinar). This gives us the equations:

$$\begin{aligned}\frac{dx}{dt} &= \alpha x(1 - \frac{x}{K}) - \beta xy \\ \frac{dy}{dt} &= \delta xy - \gamma y\end{aligned}\tag{5}$$

This new model is more realistic in that the prey population does not grow unbounded in the absence of predators. As a result, the addition of a logistic growth term also results in a third steady state point which is located at $x = K$, $y = 0$ (since the prey population exhibits purely logistic growth in the absence of predators).

Allee Effect

Another flaw of the Classic Lotka-Volterra System is its inability to account for complex ecological phenomena regarding the effect of population density on predator and prey growth rates and interactions. One such dynamic was first described by Warder Clyde Allee in (Allee) as the positive relationship between a population's average fitness to the number of individuals in that population (Livadiotis and Elaydi). Essentially, higher population densities make it easier for individuals to find mates, exploit resources, and avoid predators. The Allee Effect is generally categorized into two main types: The Weak Allee Effect, and the Strong Allee Effect (Diz-Pita and Otero-Espinar). The main distinction between these phenomena is the existence of a "critical threshold" that the population must exceed to avoid extinction. A population exhibiting the Weak Allee Effect will always display a positive growth rate in the absence of predators regardless of population size, although this growth rate does decrease as population density falls. A population exhibiting the Strong Allee Effect, on the other hand, will display a negative growth rate in the event that it falls under the critical threshold. Such species are a lot more susceptible to extinction due to this inescapable "extinction vortex".

A single species model incorporating both logistic growth and the Allee effect can be derived fairly easily by simply adding a new term $(N - m)$ to our logistic growth model (Equation 3) (Diz-Pita and Otero-Espinar), which gives us the equation:

$$\frac{dN}{dt} = rN(1 - \frac{N}{K})(N - m)\tag{6}$$

This new differential equation is said to represent the weak Allee effect if $m \leq 0$ and the strong Allee effect when $m > 0$. This is the case since a positive or zero value of m prevents the Allee effect term from ever falling below zero, preventing negative population growth as a result of this term. When $m > 0$, the Allee effect term will be negative for any x values less than m , resulting in the aforementioned extinction vortex induced by the strong Allee effect. Note that K should exceed m for both ecological and mathematical reasons.

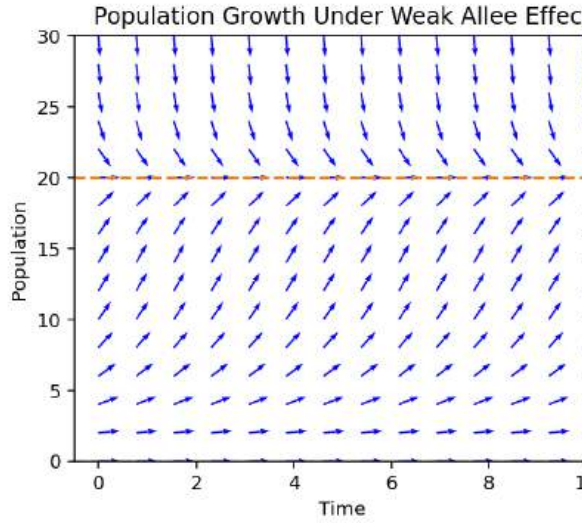


Figure 2: Slope Field modeling Allee

effect with initial values $K = 20$ and $m = 0$

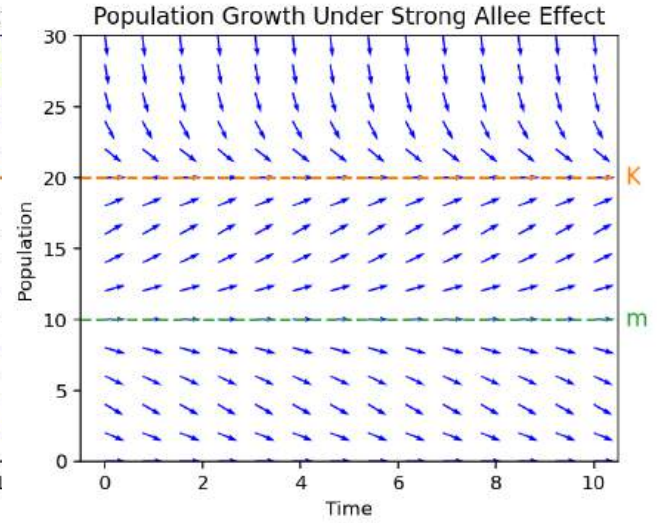


Figure 3: Slope Field modeling Allee effect

with initial values $K = 20$ and $m = 10$

These slope fields demonstrate the distinction between ODEs modeling the weak vs strong Allee effect. In Figure 2, the population eventually reaches the carrying capacity K regardless of initial size. In Figure 3, however, it can be observed that populations with $N(0) < m$ (lower than the critical threshold) inevitably go extinct due to an extinction vortex.

Likewise, the Lotka-Volterra System is often modified to incorporate the weak Allee Effect through the addition of a term which we will refer to as $A(x)$ that must meet the following requirements as a result of biological implications (Merdan):

- $A(0) = 0$ because reproduction is not possible with a population size of zero.
- $A'(x) > 0$ for $x > 0$ since the Allee Effect's limitations on growth dwindle as a given population becomes bigger.
- $\lim_{x \rightarrow \infty} A(x) = 1$ because the impacts of the Allee effect become negligible at especially high population sizes.

Since the Allee Effect is most often applied alongside logistic growth, we will multiply our Allee Effect term $A(x) = \frac{x}{B+x}$ by the growth term of our prey population. We will also make the death term in the predator growth equation quadratic to model density-dependent mortality. Applying these modifications to our logistic Lotka-Volterra System (Equation 5) yields:

$$\begin{aligned} \frac{dx}{dt} &= \alpha x \left(1 - \frac{x}{K}\right) \left(\frac{x}{B+x}\right) - \beta xy \\ \frac{dy}{dt} &= \delta xy - \gamma y^2 \end{aligned} \tag{7}$$

The addition of the Allee effect to the Lotka-Volterra System has several interesting implications on the dynamics of the model (Diz-Pita and Otero-Espinar). For example, the Allee effect often results in longer time taken for both predator and prey populations to reach equilibrium. It also results in different population values for this equilibrium.

Holling's Functional Response Models

While the aforementioned modifications effectively account for basic patterns in the prey growth rate, they inaccurately represent a linear relationship between predator/prey populations and predator-prey interactions. In reality, predators struggle to find prey as a result of low prey population densities or become saturated as a result of high prey population densities. These phenomena can be addressed by Holling's functional response models (Denny), which result in more accurate prediction of predation rates.

During the late 1950s and early 1960s, Crawford Stanley Holling came up with three main types of functional responses based on their complexity and resemblance of real world dynamics (Denny). A Type I Functional Response displays a linear relationship between prey capture rate and prey population, making it the simplest of the three. Although Holling had suggested a critical value of prey population at which the functional response would abruptly saturate, this constraint is usually ignored. This type of functional response is the one assumed in the classic Lotka-Volterra model. A Type II Functional Response also displays a positive relationship between prey population and predator-prey encounters, although it improves upon Type I in that it gradually approaches saturation as the prey population grows. Finally, a Type III Functional Response is different from Type II in that it displays acceleration of the prey capture rate at low prey populations. Note that Type IV Functional Response models have also been developed and analyzed, though they will not be covered in this paper.

$$\begin{aligned}\frac{dx}{dt} &= \alpha x - \beta y C(x) \\ \frac{dy}{dt} &= \delta x C(x) - \gamma y\end{aligned}\tag{8}$$

Using $C(N)$ to denote the capture rate in terms of prey population x , we can write the general equations for each type of functional response (Denny) which can be adapted into other models such as the Lotka-Volterra system. For a Type I Functional Response:

$$C(x) = ax\tag{9}$$

where a is a constant representing the rate of predator-prey encounters. A Type II Functional Response is modeled by:

$$C(x) = \frac{ax}{1+hax}\tag{10}$$

where h represents handling time (a measurement of how long a typical predator-prey interaction

will last). Finally, a Type III Functional response can be modeled by:

$$C(N) = \frac{ax^2}{1+hax^2} \quad (11)$$

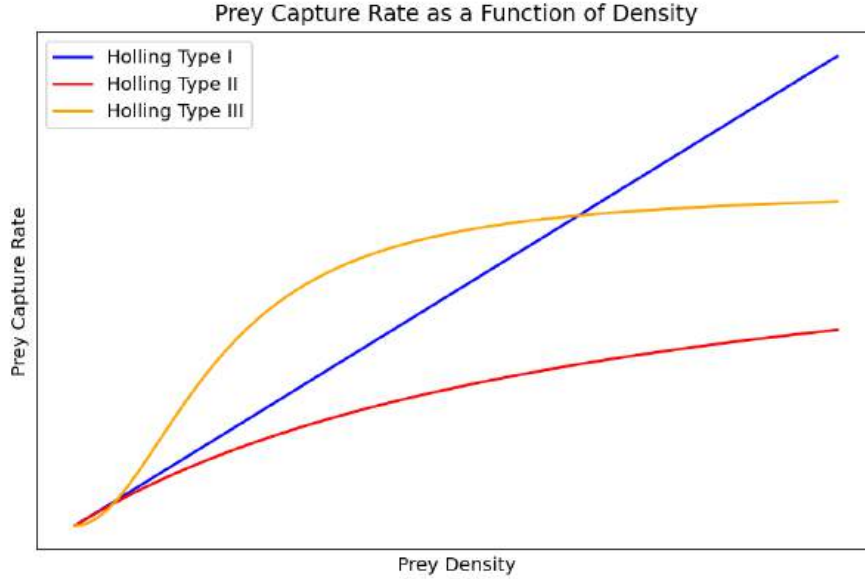


Figure 4: Holling's Functional Response Models for $a = 0.1$ and $h = 0.7$

Figure 4 displays the distinction between the different types of functional response models. It can be seen that while Type I is linear, Type II levels off (signifying predator saturation) at higher prey densities. While subtle in Figure 4, Type III displays a sigmoidal (s-shaped) curve before leveling off.

Holling's Functional Response Models are fairly easy to incorporate into the classic Lotka-Volterra system (Equation 4). As shown in Equation 8, we simply need to alter our prey death term (βxy) and our predator growth term (δxy) to include the different types of functional responses $C(N)$. Note that the Lotka-Volterra system already assumes a linear relationship between prey density and predator-prey interaction rate, rendering incorporation of Holling's Type I Functional Response unnecessary. Using substitution, we can come up with the following systems of equations.

Lotka-Volterra Model modified with Holling's Type II Functional Response:

$$\begin{aligned} \frac{dx}{dt} &= \alpha x - \beta y \left(\frac{ax}{1+hax} \right) \\ \frac{dy}{dt} &= \delta x \left(\frac{ax}{1+hax} \right) - \gamma y \end{aligned} \quad (12)$$

Lotka-Volterra Model modified with Holling's Type III Functional Response:

$$\frac{dx}{dt} = \alpha x - \beta y \left(\frac{ax^2}{1+hax^2} \right) \quad (13)$$

$$\frac{dy}{dt} = \delta x \left(\frac{ax^2}{1+hax^2} \right) - \gamma y$$

Holling's Functional Response Models affect the Lotka-Volterra system by accounting for predator saturation, helping them more accurately reflect real-world populations given appropriate assignment of constants. Equations 11 and 12 can also be further modified to incorporate logistic growth or the Allee effect.

Conclusion

In this paper, we analyzed the development and progression of various population modeling equations ranging from simple to complex. Beginning with the basic exponential growth ODE (Equation 1), we identified certain flaws and limitations of single-species models and how they can be fixed. We then introduced the classic Lotka-Volterra System (Equation 4) as the basis upon which most multi-species models are developed. The Lotka-Volterra model was shown to account for many more real-world dynamics than its single-species counterparts, producing the periodic oscillations that were observed in the wild by its creators. Next, we acknowledged the flaws and limitations of the Lotka-Volterra model and identified solutions to account for such dynamics. Logistic growth was incorporated into the classic system, preventing unbounded prey population growth in the absence of predators. The strong and weak Allee effects were also introduced, allowing for equations to model phenomena such as extinction vortices and reduced population growth rates at low densities. Finally, Holling's Functional Response Models were introduced as a way to account for nonlinear relationships between predator-prey interaction rates and population densities (e.g. predator saturation).

Overall, progress in the field of population dynamics is extremely promising as shown by the models analyzed in this paper (and countless others). As mathematicians and ecologists work alongside to develop models that account for even more real-world population dynamics, we will be even closer to being able to mathematically describe real life ecosystem interactions.

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Beneath the Glam: How Social Media Marketing Influences Consumerism Amongst Teenagers in the UAE By Layane Fattah

Abstract

Digitalization has profoundly transformed the global fashion industry, merging social media marketing, e-commerce, and youth consumption. Despite extensive research, a gap exists in understanding how emerging technologies and digital platforms influence purchasing decisions among UAE youth. This study explores consumerism in the UAE's digital retail, focusing on how budget e-commerce platforms like Noon and Shein reshape price sensitivity and consumer engagement amongst Gen Z. The research examines psychological and economic factors driving online fashion consumption, revealing how social media marketing and digital platforms manipulate consumer behavior. This paper argues that brand perception, influencer marketing, and fashion trends are crucial beyond price. The study explores consumer motivations in the UAE's digital marketplace using mixed methods, including qualitative case studies, literature reviews, and comparative brand analyses (Zara vs. Shein). Integrating consumer psychology, marketing strategies, and technological trends, this research paper offers crucial insights into digital consumerism. It illuminates the relationship between social media marketing and youth purchasing behavior, providing actionable recommendations for businesses to engage with the UAE's emerging digital consumer landscape.

Keywords

Social media marketing, Consumerism, UAE youth, E-commerce, Fast fashion, Price sensitivity

Introduction

While artificial intelligence is transforming industries globally, its involvement in the luxury fashion sector, specifically in developing markets like the UAE, remains underutilised. This study seeks to raise awareness of the environmental impact of fashion trends and examine practical methods to reduce waste, as these patterns continue to emerge rapidly, increasing an already high level of consumerism (Na'amneh, 2021). The research offers an adaptable structure that can be applied to additional general consumerism-related issues that remain unsolved by considering various contributing factors.

The burgeoning influence of Artificial Intelligence (AI) is undeniably transforming global industries. However, its profound capabilities within the luxury fashion sector, particularly in dynamic emerging economies such as the United Arab Emirates (UAE), are still remarkably untapped. While extensive research has delved into the efficacy of AI-driven strategies within established Western markets, a significant void persists in comprehending how these advanced technologies genuinely reshape consumer behavior within the UAE's burgeoning luxury market. This deficit in understanding is especially critical when considering the escalating environmental repercussions of rapid fashion trends and the resulting substantial waste generation.

A compelling imperative underpins this research endeavor to bridge this knowledge gap. By doing so, it aims to deliver actionable and practical methodologies designed to mitigate those above environmental and consumption-related issues and introduce a flexible and adaptable framework. This innovative framework is envisioned to transcend the immediate scope, offering a versatile tool for addressing a broader spectrum of challenges associated with contemporary consumerism, thereby fostering more sustainable practices within the luxury market and beyond. How has the rise of budget e-commerce platforms (like Noon and Shein) shifted price sensitivity among UAE youth? Do rising apparel prices increase purchase urgency rather than reduce demand in the UAE e-commerce? Do customers in the UAE rely more on *social signals* than *price changes* to guide purchase decisions in fashion e-commerce?

The research question, “How has the rise of budget e-commerce platforms (like Noon and Shein) shifted price sensitivity among UAE youth?” was inspired by how easily consumerism has become part of daily life, primarily through the convenience of shopping online from the comfort of one's own home. This study explores consumerism and purchase behaviour among UAE youth, discovering factors that can influence purchases and customer behaviour across e-commerce platforms. The focus is on examining the aspects of consumerism using different quantitative methods to understand the issues and consider different improvements that can be made to reduce the psychological aspects of consumerism.

Comparing different studies, Al Jamil and Ismail (2022) utilize quantitative methods to emphasize the comparison between commercial social media and e-commerce platforms. The outcomes of numerous analyses show that e-commerce platforms are more common than commercial social media, highlighting the role played by unethical advertising tactics and unprofessional customer support. E-commerce platforms are easy to use and navigate, and simple online payment methods may encourage more people to use them, increasing the number of customers.

Methodology

The research methodology employed in this study aims to explore how the rise of budget e-commerce platforms shifted prices amongst UAE youth. The literature review analyzes studies focused on Gen Z price consciousness and fast e-commerce. Using a case study comparison between Shein vs Zara in the UAE, price tracking on different platforms for 4 weeks, the research contrasts two prominent fast fashion brands, Zara and Shein. Zara is known for its better quality materials and premium pricing, while Shein offers lower quality products at significantly cheaper prices. This comparative approach provides valuable insights into how pricing strategies and perceived value affect consumer behavior in the digital retail landscape.

The target population for this study comprises UAE youth, specifically Gen Z (ages 13-28). The study will focus on analysing consumer purchase behaviour on e-commerce platforms. This research will also examine and compare the purchasing patterns of two major fast fashion brands, Zara and Shein, highlighting the contrast between quality-driven and price-driven

consumer choices. A qualitative approach will be established, incorporating a literature review and a case study analysis to compare the two brands and their influence on consumer behavior.

Qualitative data were examined through a combination of literature review and case study analysis, with a particular focus on Zara. Both SWOT analysis and detailed case studies were employed to enhance the reliability and accuracy of the findings. This involved a comprehensive evaluation of Zara's strengths, weaknesses, opportunities, and threats, alongside an overview of the company's background and development. The methodology was carefully designed and well-applied, allowing for an in-depth exploration of leadership practices within e-commerce platforms through robust qualitative methods.

Literature Review

This study involves a literature review that looks at a range of relevant case studies which fall compatible with the research topic and its primary questions, to provide an in-depth understanding of the problem at hand. By offering evidence-based perspectives on the developing issue, these case studies provide insightful data that reinforces the validity of the conclusions. The literature review is essential for presenting a range of perspectives from different writers and eras, enhancing the analysis's accuracy and thoroughness. A thematic approach focuses on consumerism and purchasing behaviors concerning social media marketing and e-commerce platforms. The convenience offered by electronic commerce and artificial intelligence has led to a surge in their use, especially among young people in the United Arab Emirates. Al Jamil and Ismail (2022) utilize a thematic approach, primarily focusing on consumer behavior and buying behaviors regarding social media marketing and e-commerce platforms. Due to these platforms' simplicity and efficacy, digital commerce and artificial intelligence use have risen, particularly among youths in the United Arab Emirates, as these industries continue to grow and become increasingly accessible. Meanwhile, the rapid advancement of social media marketing has demonstrated a particular impact, with Generation Z being the most susceptible population due to their significant interaction with online content.

This literature review will examine how pricing and product quality interact and how e-commerce platforms affect purchasing decisions. It additionally intends to investigate how online platforms may significantly impact consumer perceptions and decisions regarding whether or not to buy advertising strategies, consumer feedback, and social media influence.

Table 1: Selected Literature Review

Study	Methods	Country	Factors	Findings
Alnahhal et al. (2024)	Qualitative	UAE	-Consumer buying behaviour -product quality -Importance and impact of lower	1. Results prove that product quality is more important than lower prices. 2. Highly educated consumers appreciate less crowded and well-designed hypermarkets 3. Studies show that married people tend to

			prices	care more about prices than other factors, meaning their target is to find items at the best prices they can get.
Al Jamil and Ismail (2022)	Quantitative	Oman	- customer service quality - web design - delivery costs - easy navigation	1. Studies reveal that e-commerce platforms are most preferred over commercial social media, which highlights the role of unethical marketing practices, unsystematic delivery costs, and unprofessional customer service quality. 2. The study shows that the intersection between product prices, quality, and information builds trust through professionalism, responsiveness, and empathy, which enhances customer service quality. 3. The easy navigation and online payments of e-retailing platforms can influence more people to use them, increasing the number of buyers on their platforms.
Seetharaman et al. (2017)	Quantitative	UAE	-transaction cost -culture -local regulation -trust	1. The results show that to gain customer trust, these companies must improve the quality of their websites and have reviews from previous customers to show that their websites are genuine. 2. Research proves that the popularity of mall culture is one of the factors why there is no rapid growth in e-commerce platforms
Na'amneh, (2021)	Qualitative	UAE	-easy navigation -social media marketing - user-friendly by design	1. Studies show that most students invest a significant amount of their available resources (e.g, time, money, and effort) on consumption 2. Results prove that social media platforms play an influential role in encouraging online shopping and brand interaction amongst young customers
Waqar (2016)	Quantitative	Finland	-social media marketing -easy navigation	1. Studies show that social media marketing can skyrocket a business by influencing people in persuasive ways

			-popularity of the product	2. Research proves that after seeing ads online, consumers subconsciously buy things after seeing information about their favorite brands

Social media marketing significantly impacts consumer purchasing behavior, according to a review of multiple research studies. Personalized advertisements alongside their favorite fashion brands, influencers, and models elements which increase engagement and purchase behaviour, often affect consumers. Based on research, many consumers prioritize perceived value over price and are willing to pay more for better-quality apparel (Alnahhal et al., 2024). In addition, it has been established that influencer-driven content, such as brand campaigns and promotional videos, significantly boosts customer purchases and business visibility, highlighting the decisive role that digital influence plays in increasing sales.

It is apparent when comparing different studies that Alnahhal et al. (2024) concentrate on comparing higher-cost and premium clothing with less expensive and lower-quality clothing, evaluating data to determine which consumers prefer to buy. To the data and generate accurate results, Alnahhal et al. (2024) employed qualitative methods. The results demonstrate that consumers appreciate higher-quality goods at premium prices, making assessments crucial. Results consistently demonstrate that highly educated consumers prefer well-designed, less crowded hypermarkets, making e-commerce platforms the perfect solution. However, research studies indicate that married individuals with kids tend to be more price sensitive, seeking the best feasible deal.

Comparing different studies, Al Jamil and Ismail (2022) utilize quantitative methods to emphasize the comparison between commercial social media and e-commerce platforms. The outcomes of numerous analyses show that e-commerce platforms are more common than commercial social media, highlighting the role played by unethical advertising tactics and unprofessional support for customer support platforms. Easier to navigate and simple online payment methods may encourage more people to use them, the number of customers.

Case Study Framework

The retail company Zara Inc. is one of the world's most successful fast fashion brands. Founded in 1975, with its bold beginning of the rise of the concept of “fast fashion”, Zara has experienced rapid growth and expansion into new markets across multiple divisions (Zara, 2025). Although with an increase in customer demands and rising competition, Zara has faced an inadequate supply chain, due to having over 2000 retail outlets worldwide, yet it continues to depend primarily on its central production facilities to supply clothing for all of these outlets. This SWOT analysis examines the company's strengths, weaknesses, and background information, working towards solutions to maintain the company's strengths and rapid growth.

The analysis of Zara Inc.'s current situation reveals key factors contributing to its challenges. A SWOT analysis reveals many of its strengths, such as its global reach. Zara started

small for the first few decades after it was established. However, it has expanded to 96 countries, and is currently operating 2270 retail outlets across many different regions. The SWOT analysis also reveals that one of Zara's many strengths is its fast and efficient production, which releases a new clothing collection every two weeks. Although offering only a limited quantity of each design, the brand creates a sense of exclusivity that customers find desirable.

ZARA

Background

Zara, known for its fashionable yet reasonably priced clothing, was founded in 1975 and has evolved into a significant global fashion retailer, operating over 2000 stores across 96 countries. Zara's innovative business model, which focuses on fast fashion, substantially contributes to its success. Zara effectively monitors and adapts to evolving fashion trends, introducing new styles to its stores every two weeks. The company's ability to rapidly respond to changing fashion trends and its strong focus on customer preferences have helped it maintain a leading position in the fashion industry and operate a vertically integrated supply chain that enables rapid production and distribution of its products. Established in 1975 by Amancio Ortega and Rosalía Mera, Zara has grown from a single store in A Coruña, Spain, into one of the world's largest and most influential global fashion retailers. Today, it boasts an impressive presence with over 2,000 stores strategically located across 96 countries, making its fashionable yet affordable apparel accessible to a vast international consumer base.

The cornerstone of Zara's phenomenal success lies in its pioneering fast-fashion business model. This innovative approach is characterized by a relentless commitment to continuous monitoring of the latest fashion trends and an unparalleled capacity for swift adaptation. Unlike traditional fashion cycles that might involve months of lead time, Zara's agile system allows for bi-weekly introductions of new styles and collections. This rapid turnaround ensures that the brand remains at the cutting edge of fashion, consistently offering consumers the most current looks.

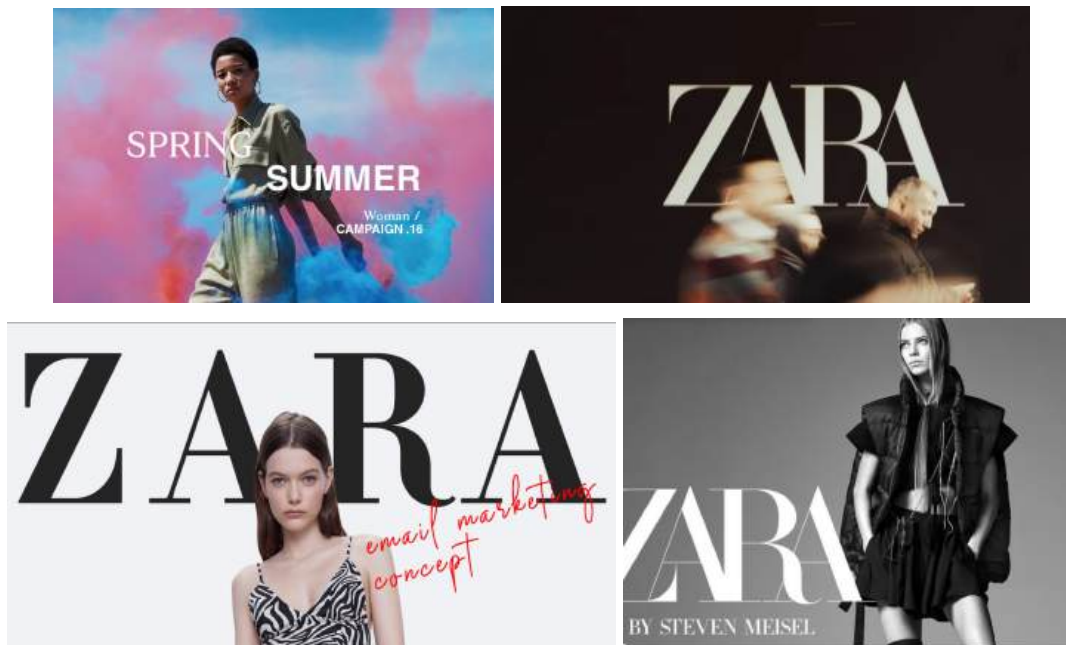
Zara's vertically integrated supply chain amplifies this exceptional responsiveness to evolving customer preferences. This means the company controls a significant portion of its production process, from design and manufacturing to distribution and retail. This integration dramatically reduces lead times, minimizes waste, and allows for precise control over quality and inventory. By owning and operating most of its supply chain, Zara can quickly translate runway trends into wearable, affordable garments that hit stores in weeks rather than months. This efficient and streamlined operation has enabled Zara to maintain and significantly enhance its prominent standing within the highly competitive global fashion industry. Its ability to democratize high fashion by making it accessible and affordable has solidified its position as a true industry leader.

Strategy

A significant part of Zara's success can be attributed to its smart marketing strategy. By utilizing customer insights and data-driven analysis, Zara receives new inventory twice a week, allowing it to adapt its designs in response to emerging fashion trends. Zara's collection is a well-balanced combination of the latest trends, practical designs, and flexibility. It provides a broad selection of clothing to meet the needs and desires of its customers. The 4C concept was introduced by Bob Lauterborn in 1990 as an updated version of the 4Ps. Lauterborn's marketing concept centres on the customer, emphasizing the 4Cs: meeting consumer needs, balancing costs to satisfy customer expectations that are profitable for the business, ensuring convenience, and building strong communication between the brand and its audience. This marketing strategy mainly targeted 24-45-year-old educated people. The company promotes itself through its products, store aesthetics, and social media presence.

Zara's highly successful marketing strategy predicates unparalleled responsiveness to emerging fashion trends and a profound understanding of customer needs. This agile methodology is facilitated by a distinctive supply chain model, which enables Zara to replenish its inventory twice weekly. This rapid replenishment cycle allows the company to adapt its designs swiftly based on real-time customer insights, garnered through sophisticated data analysis from sales, in-store feedback, and online interactions.

The principal objective of this strategy is to offer a comprehensive and continuously updated selection of apparel that seamlessly integrates the latest trends with practical designs and inherent flexibility for the wearer. This dynamic inventory ensures that customers consistently discover novel and pertinent items, driving repeat visits and sustaining the brand's reputation as a trendsetter.



Implicitly, Zara's strategy demonstrates strong alignment with Bob Lauterborn's influential 4Cs concept, introduced in 1990, which redefined the traditional marketing mix (Product, Price, Place, Promotion) from a customer-centric viewpoint:

- **Consumer Needs (vs. Product):** Zara's operational framework is constructed around identifying and satisfying consumer desires at an accelerated pace. Rather than dictating trends, they react to and amplify them, ensuring their offerings meet consumer demand.
- **Cost (vs. Price):** Zara meticulously balances costs for both the customer and its own business profitability. While providing trendy items, they maintain competitive pricing that renders fashion accessible, ensuring efficient production and distribution to secure healthy margins.
- **Convenience (vs. Place):** Zara ensures convenience through an extensive global retail presence of strategically situated stores in high-traffic areas, complemented by a robust and user-friendly e-commerce platform. This multi-channel approach facilitates effortless customer access to their products.
- **Communication (vs. Promotion):** Instead of heavily relying on traditional advertising campaigns, Zara cultivates robust communication between the brand and its audience primarily through its products, the inviting and contemporary aesthetics of its physical stores, and an engaging presence across various social media platforms. The product *is* the message, continuously reflecting current styles and consumer preferences.

This sophisticated strategy primarily targets a demographic of educated individuals aged 24-45, who are fashion-conscious, digitally proficient, and value rapid access to current styles. Zara's marketing communication is characterized less by explicit promotion and more by the immersive brand experience conveyed through its constantly evolving product lines, the curated atmosphere of its retail spaces, and its interactive and visually driven social media engagement, which enables direct feedback and real-time trend monitoring.

Impact

Today, Zara operates 2,264 stores in 96 countries, strategically located in key urban centers (Zara, 2025). What began as a small shop in Spain has become the world's leading fast-fashion retailer and Inditex's flagship brand. The brand's ability to involve customers in the design process, combined with its streamlined supply chain, sets it apart and provides a strong competitive edge.

Starting as a modest establishment in Spain, Zara has become the global preeminent fast-fashion retailer and Inditex's flagship brand. Zara maintains an extensive network of 2,264 stores strategically positioned in major urban centers across 96 countries, which highlights its commanding presence within the retail sector.

Zara's distinctive competitive advantage stems from its capacity to integrate customers directly into the design methodology. This customer-centric methodology, complemented by a highly optimized supply chain, enables the brand to adapt swiftly to emergent fashion trends and

shifts in consumer preferences. This agile framework distinguishes Zara from its rivals, facilitating the rapid introduction of new store collections and consistently upholding its leadership in the fast-fashion industry.

Analysis and Insights

What distinguishes Zara from its competitors is its relentless drive for innovation while maintaining high quality and accessible pricing. Its responsive fast-fashion model delivers fresh designs to stores every week, securing its position as a go-to brand for fashion-forward consumers around the globe. However, this strategy has a significant impact on consumer behavior. It encourages shoppers to buy more often than they do at other stores. By introducing new collections every two weeks and keeping prices low, Zara creates a sense of urgency and variety that keeps customers returning. This continuous buying cycle builds brand loyalty, crucial for the company's growth and success worldwide. Zara's remarkable success within the global fashion industry can be attributed to its unwavering commitment to innovation and its ability to deliver high-quality products at accessible price points. The core of its competitive advantage resides in its highly responsive fast-fashion model. This strategy enables Zara to introduce fresh, on-trend designs to its stores worldwide every week, solidifying its reputation as a premier destination for fashion-forward consumers.

This dynamic approach, however, profoundly influences consumer behavior. Zara cultivates a powerful sense of urgency and constant variety by consistently offering new collections and maintaining competitive pricing. This encourages shoppers to frequent and purchase from Zara more often than they would from other retail brands. The rapid turnover of inventory, coupled with competitive pricing, incentivizes customers to make impulse purchases and continually refresh their wardrobes. This continuous cycle of new arrivals and consistent purchasing drives immediate sales and plays a crucial role in building and reinforcing strong brand loyalty. Customer engagement and loyalty are paramount to Zara's ongoing growth and continued global expansion and success.

Implications

This investigation advances scholarly understanding by furnishing an empirical elucidation of the intricate interplay among price sensitivity, product quality, and consumer decision-making catalysts within the e-commerce domain. It transcends a simplistic perception of price as the sole determinant of purchasing behavior, incorporating factors such as quality, accessibility, and customer service. The salient finding is the nuanced influence of these elements on purchase resistance, particularly among younger demographics, and the efficacy of promotional strategies, including sales and limited-time offerings, in mitigating such resistance. This predominantly empirical contribution provides data-driven insights into contemporary online shopping habits.

Prior research has extensively explored price sensitivity in isolation or concentrated on individual factors influencing consumer behavior. Nevertheless, a notable lacuna persists in

integrated studies examining how price interacts with perceived quality, accessibility, customer service, and specific e-commerce marketing tactics (e.g., sales, limited drops) to facilitate or deter purchases. This study directly addresses this void by proposing a holistic framework that integrates these previously disparate aspects, offering a more comprehensive depiction of the decision-making process within the digital retail environment.

These findings offer commercial entities actionable insights for optimizing pricing strategies, product positioning, and marketing campaigns. Businesses can ascertain how to equilibrate price competitiveness with perceived quality and customer service, rather than exclusively competing on cost. They can also leverage the understanding of "decision-making triggers," such as sales and limited-time offers, to strategically influence purchasing behavior. For policymakers, this research underscores the importance of fostering equitable competition in e-commerce, potentially informing regulations concerning transparent pricing, consumer protection, and even the psychological impact of aggressive marketing tactics on online shoppers. Retailers can utilize this information to design more effective user interfaces that cater to diverse age groups, particularly by addressing the resistance to shipping fees observed among older individuals.

Beyond its academic and sectoral relevance, this study contributes to resolving real-world challenges pertinent to consumer welfare and sustainable consumption in the digital era. Companies can mitigate superfluous production and waste by comprehending why consumers resist specific purchases, aligning with broader sustainability objectives. The research also touches upon aspects of digital inclusion by illuminating the varying comfort levels of different age groups with e-commerce platforms. Ultimately, by elucidating the complexities of online consumer behavior, this study contributes to developing a more efficient, equitable, and user-friendly digital marketplace, fostering improved interactions between businesses and consumers in the perpetually evolving e-commerce landscape.

Conclusion

While competitive pricing undeniably serves as a primary determinant in consumer choices, the Zara case reveals a more nuanced picture. The perceived value and continuous novelty inherent to brands like Zara establish a distinctive dynamic. This dynamic encourages frequent acquisitions and cultivates a strong brand loyalty, even in scenarios where direct price comparisons superficially favor ultra-budget alternatives offered by platforms such as Noon and Shein.

Consequently, this suggests that factors beyond monetary cost influence this demographic's price sensitivity and overall purchasing decisions. These critical influencing factors include, but are not limited to, product innovation, the constant influx of new styles, and the immersive brand experience that Zara provides. Unlike purely budget-driven platforms, Zara offers a blend of aspirational design, timely trends, and a tangible in-store or online experience that resonates deeply with young consumers, often leading them to prioritize these elements over

the absolute lowest price point. This indicates that while budget e-commerce platforms have undeniably introduced a new level of price competitiveness, they have not entirely eroded the desire for fashion newness, brand connection, and perceived quality, which Zara effectively leverages to maintain its market position and influence consumer behavior among UAE youth.

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Current Challenges and Technology Gaps for Rocket Landing Mechanics

By Natalia Konchylaki

Abstract

Rockets push the boundaries of technology, but every successful launch depends on solving a series of complex engineering problems. This paper examines the performance and limitations of various rocket engine types, emphasizing how their design influences efficiency and mission applicability. It also explores how aerodynamic shapes can impact a rocket's stability, speed and strength during its flight. The study compares landing methods, including parachutes, streamers and gliders, to understand which systems work best for a safe recovery on Earth. Finally, common failures related to engines, structural stress, and reentry dynamics are analyzed to identify critical challenges in modern rocketry. By bringing these aspects together, this research aims to uncover smarter and more reliable ways to design rockets for the future.

Keywords

1. Rockets,
2. Propulsion,
3. Landing,
4. Reentry,
5. Technology gaps,
6. Stability

Introduction

Ever since the dawn of civilization, the human race has been driven to explore and create, and rocket science is a natural extension of that. From the early Chinese fire arrows to the National Aeronautics and Space Administration's (NASA) newest Orion rocket, the journey of rockets has undergone periods of rapid invention and significant challenges. While propulsion and landing mechanics often steal the spotlight, one of the most complex and pressing challenges in modern rocketry lies in the final phase of any mission: landing.

The science and engineering behind rocket landing mechanics begin with the fundamentals of propulsion. The ability to land rockets safely and reuse them depends not only on powerful and reliable engines but also on durable yet lightweight structures that can withstand high stress during descent. Despite impressive progress in recent years, challenges still remain, particularly in optimizing engine performance during descent, ensuring structural stability, and improving control systems.

This study examines these technology gaps, emphasizing the roles of propulsion efficiency, structural resilience, and integrated guidance-control systems in successful rocket recovery. To understand these issues, it is important to begin with the basics of propulsion and rocket motion, which are rooted in Newton's Third Law. Yet, landing a rocket involves much more than just reversing thrust. It is a highly complex process that combines aerodynamics, navigation, materials engineering, and much more. Every component must work perfectly with one another to achieve a smooth and accurate descent.

Reviewing landing failures, from early experimental flights to modern vehicles like SpaceX's Starship, highlights some of the most common errors in rocketry. These usually include engine misfires, structural collapse, and navigation system failures. Each failed landing provides

engineers with new insight into what needs further improvement, especially in the coordination between a rocket's physical design and its software-controlled systems. The purpose of this study is to identify the primary limitations in current landing technologies and to provide a foundation for future advancements.

1. Rocket engines, their different types and rocket structure.

1.1 Sub-Theme: Rocket Engines

The ability of rockets to move through the air, as well as escape the Earth's gravity and travel through space is greatly based on advanced propulsion systems that rely on engineering and fundamental laws of physics.

One of the most significant laws of physics concerning rockets and their movement is undoubtedly Newton's third law of motion. According to this law, every action results in an equal and opposite reaction, which explains how rockets generate thrust by expelling exhaust gases at extremely high speeds. More specifically, a common rocket engine consists of five main parts: An oxidizer tank, a fuel tank, pumps, a combustion chamber and a nozzle.

Each and every one of those parts has a specific and unique role in the propulsion of a rocket. The oxidizer tank carries the type of oxidizer needed in order to burn fuel quickly. The fuel and oxidizer tank release their contents into the pumps, where they are mixed together. Once the two liquids are fully dissolved, they are moved over to the combustion chamber. In the combustion chamber, an igniter is lit up and the mixture of oxidizer and fuel begins to burn, producing hot exhaust. This hot exhaust then travels over to the nozzle where it forcefully springs out, creating thrust and giving the rocket the ability of moving upwards towards the sky.

1.2 Sub-Theme: Rocket Engine Types

Over the years, scientists and engineers have combined their skills and knowledge to construct and put into practice various designs of rocket engines that can accommodate the diverse needs of space travel, each offering distinct benefits and limitations. Different rocket engines are developed to fulfill specific roles, depending on the unique requirements of each mission.

Solid-fuel rocket engines, among the oldest rocket designs, are highly valued for their simplicity and low cost. These are also characterized as more reliable, since there are no moving parts in the engine. Solid rocket engines use propellants made by combining fuel and oxidizer into a solid mixture. Throughout takeoff, the propellant burns very quickly, thus creating strong thrust and as a result, the rocket takes off onto the sky.

Liquid fuel rockets comprise the most commonly-used type of rocket engine. This type of engine is used from powering rockets to launching spacecraft. Unlike solid-fuel rocket engines, these engines store their fuel and oxidizer into separate tanks. These liquids are then pumped onto the combustion chamber, where they are mixed and eventually burnt. These are turned into hot exhaust, which is pushed out through a nozzle at extremely high speed, thus creating thrust.

Hybrid engines combine characteristics of both liquid and solid fuel engines. They use solid and liquid fuel/, which can be stored in a casing and a liquid oxidizer. The solid and liquid fuel are pumped into a combustion chamber, where they are mixed and, eventually, burnt. Hybrid engines are said to be more efficient than solid-fuel engines and more easily controlled than liquid-fuel engines. Even if these types of engines provide a great balance between dependability and adaptability, they are still not widely used due to their complex design, inconsistent thrust, and higher cost compared to solid and liquid engines.

A more advanced technology that has been introduced to rocket engineering are ion rocket engines. This type of engine generates thrust by ionizing particles. To be more exact, ion rocket engines use electricity to speed up charged particles or ions. These ions or particles are shot out of the engine's nozzle at very high speeds. Many describe this type of engine as slightly inefficient, as it cannot produce that much thrust. Despite the fact that it generates far less force than a traditional chemical-powered rocket engine, its fuel efficiency makes it extremely durable and ideal for long-term space missions.

Nuclear thermal rocket engines use heat from a nuclear reactor in order to warm up a propellant such as hydrogen. This hot propellant produces exhaust that is pushed through the rocket engine's nozzle at extreme speeds. In spite of the engine's sheer power, they are severely complicated, are exceedingly expensive to build, and have not yet been proven very adaptable.

1.3 Sub-Theme: Rocket Structure

The structure and shape of a rocket are carefully designed to align with its propulsion system, ensuring high efficiency, performance and stability during flight. A rocket's shape helps it move through the air and reach space efficiently. A rocket's cone-shaped design is a great method to reduce drag, helping it move smoothly through the air. Sharper cones are preferable when travelling at high speeds. Rocket fins play a crucial role in maintaining stability and securing a greater and more controlled flight. Finding the right balance between fin size, placement and drag is imperative for a rocket's exceptional performance.

However, shape alone is not enough. Rockets must also be built from strong, durable materials in order to endure a flight heading outside of space. Titanium/Aluminium/Lithium alloys provide the rocket with strength and corrosion-resistance, making them ideal for fuel and propellant tanks. Moreover, carbon composites, as well as ceramic matrix components provide excellent heat resistance and are perfect for use in nozzles and heat shields. Nickel alloys, like Inconel, and niobium can withstand extreme heat and oxidation, and can be used in high-engine-temperature parts, such as combustion chambers and nozzles. Ablative materials ensure a safe rocket re-entry by eroding to manage heat during the process and reinforced polymers provide flexibility, insulation and sealing for the rocket. Lastly, hydrogen-resistant alloys can prevent embrittlement in cryogenic conditions, ensuring great durability in space missions. The collective combination of both structural designs and methods, as well as all the materials used in different parts of the rockets, ensure a rocket's ability to withstand extreme and harsh conditions during space travel, while ensuring both performance and safety.

2. Rocket Landing Mechanics.

2.1 Sub-Theme: Overview of Rocket Landing Methods

Landing a rocket back on Earth from space is one of the most complex challenges in aerospace engineering. Unlike traditional rockets, that are discarded after being launched, reusable rockets rely on a controlled and safe return to Earth, by using a combination of landing methods. Precise control, continuous real-time adjustments, and a thorough understanding of certain physics principles are necessary to achieve a successful and controlled descent. These factors also ensure a safe and smooth landing for both the rocket and the astronauts inside them. Rocket landing techniques vary, each of them designed to ensure a secure and safe and controlled landing back to Earth. Some of these techniques include parachute systems, streamers and gliders.

2.2 Sub-Theme: Parachute Landing Systems

Parachutes have long played a vital role in providing a secure descent when it comes to rockets during different space missions. Different types of parachutes serve different purposes throughout the landing of a rocket. Specifically, there are four different types of parachutes that are imperative for securing a safe landing back on Earth. These include drogue parachutes, main parachutes, pilot parachutes, and ballistic parachutes.

As far as drogue parachutes are concerned, these are deployed first, as a means of stabilizing, as well as decelerating the rocket while it is still travelling at extremely high speeds, during its descent. A great example of the use of drogue parachutes are in NASA's Orion spacecraft. Despite the landing not being exactly successful, this mission clearly depicts how beneficial the use of drogue parachutes can be.

The main parachutes of a rocket operate once the drogue parachutes have fulfilled their duty. These are larger canopies, meaning they are greater in size, and they open at lower altitudes. This helps further slow down the rocket's high speeds, preparing it for a safe landing on the ground.

Pilot parachutes help extract larger canopies, while ensuring smooth deployment. Conversely ballistic parachutes have been designed for deployment during emergencies, by using small charges in order to deploy the canopy, and decelerate in a faster manner.

While these parachute systems are highly effective on Earth's atmosphere, they may present certain limitations when it comes to planets with a thin atmosphere, such as Mars. Here, further technologies are needed, such as retropulsion and airbags to ensure a safe landing on the ground.

2.3 Sub-Theme: Streamer Landing Systems

Streamer landing methods provide a simple and effective way of landing a rocket back on Earth. Unlike parachutes, which create drag in order to slow the speeds of the descent, streamers manage to generate just adequate resistance that slows the rocket down without going to extreme

limits. Streamers are usually made from lightweight, yet durable materials, such as ripstop nylon or crepe paper, which have the ability to be easily stored in a rocket.

Once streamers reach a certain altitude, they unfurl and generate aerodynamic drag, thus controlling the rocket's descent. They are mostly beneficial to use in smaller rockets, as they require much less space than parachutes do, and can easily withstand wind by reducing drift. However, they are not ideal for implementing into larger and heavier rockets, as they cannot create enough drag to ensure a soft and smooth landing on the ground. Selecting the right size and material is undoubtedly crucial to balance the decent speed while having a safe recovery.

2.4 Sub-Theme: Glider Landing Systems

Glider landing systems are an alternative, and innovative approach for safely returning rockets back to Earth. These use several aerodynamic principles. Instead of relying on parachutes or streamers, these systems provide rockets with wings or stabilizing surfaces, which transform it into a type of glider, once it reaches peak altitude above the Earth's sea level. Throughout the rocket's descent, aerodynamic lift is used. This controls its speed and direction and glides it smoothly towards the ground. This glider method is ideal when a smooth and soft landing is required, especially when recovery in a specific area is necessary.

Glider landings provide more control and accuracy than traditional parachute recovery methods do, thus making them particularly useful for reusable rockets or experiments that must land in a specific location. Despite that, careful design is crucial in order to ensure proper stability and eventually control during its descent phase. In conclusion, glider landing systems offer a highly controlled and precise recovery method, making them excellent for space missions that demand accuracy and safety.

2.5 Sub-Theme: Conclusion

Rocket landing mechanics are undoubtedly essential for safely and effectively returning a rocket back to Earth or to other destinations. Whether using parachutes, streamers or gliders, each system is designed to ensure stability, precision and reusability. As space exploration advances, these technologies will continue to evolve, paving the way for more sustainable and effective rocket recovery methods.

Methods

In order to effectively analyze the current challenges rockets are facing, this paper uses five key criteria including descent and landing precision, system reliability and coordination, engine performance during landing, structural strength, as well as reusability. These elements provide a consistent and focused method for evaluating how various rockets perform throughout their landing process. (See Table 1, page 16)

Results

Analyzing the results of past rocket landings is crucial because it reveals how designs and technologies function to practice. This analysis helps identify what works effectively and what challenges remain, allowing engineers to learn from past experiences. By understanding these outcomes, researchers can pinpoint specific areas for improvement, support future technological advancements and improve the overall safety and efficiency of rocket landing systems.

1. Falcon 9 (SpaceX)

This rocket, with fully reusable heavy-lift systems, had over 250 successful rocket landings thanks to accurate and precise descent control, its strong Merlin engine throttling, and well-integrated systems. Small issues such as leg deployment have been resolved over time. Also, its structural design supports frequent reuse (SpaceX, 2025;).

2. Terran 1 (Relativity Space)

Landing systems are not yet fully developed, but Terran 1 focuses on throttleable engines, as well as innovative 3D-printed designs and structures that can handle durability and stability challenges (Relativity Space, 2025;)

3. Space Shuttle Solid rocket boosters (NASA)

Despite the fact that these boosters failed to perform powered vertical landings, they were recovered from the oceans with the use of parachutes, and were reused multiple times. This depicts their robust and stable design, but also their reliable recovery procedures (NASA,2025;).

4. Saturn V (NASA)

Although Saturn V is not a reusable rocket, it demonstrated remarkable structural integrity and powerful engine control to safely launch and recover. Its designs have now become standards for heavy-lift rockets with controlled stage descent (NASA,2025;).

5. New Shepard (Blue Origin)

Blue Origin's New Shepard has successfully become a leader in the reusable rocket industry and is most known for its great precision in landings, quick refurbishment and renovation, and its highly advanced guidance systems (Blue Origin, 2025;)

In this table all the rockets mentioned above will be evaluated based on how much they adopt each of the criteria mentioned in the methods. A scale of 0-5 will be used with 5 being a criterion being fully adopted. (See Table 2, page 16)

Falcon 9 constantly achieves high scores due to its precise vertical landings, dependable engine performance and effective system reliability. Its structure also supports multiple uses, making it one of the most reusable and dependable rockets today.

Space Shuttle SRBs: The Space Shuttle's solid rocket boosters were very strong and recovered reliably, using parachutes, whereas they didn't have powered landings, which led to lower scores in engine performance and landing accuracy.

Terran 1: Terran 1 was an early reusable rocket attempt that struggled with landing success. Its engine reliability and system coordination were limited, and reusability turned out to be low, thus reflecting the technical challenges faced during its initial launches.

3.Challenges and common errors in rockets

3.1 Sub-Theme: Rocket Engine Failures

Rockets are some of the greatest masterpieces of modern engineering, but even the most carefully designed ones are prone to errors that can lead to an entire mission failure. From miscalculations in thrust and thrust and stability, to malfunctions concerning the software and structure of a rocket, a great variety of issues can come to light at any stage of the rocket's journey. Common problems include engine failures, structural failures, as well as challenges when re-entering the Earth's atmosphere. These mistakes, whether stemming from design and structure flaws, environmental influences, or human errors, emphasize the complexity of rocket development and the continuous necessity for innovation and testing, to enhance reliability and mission success.

Rocket engines are undoubtedly vital for space missions, but their operation in extreme conditions exposes them to a variety of failure risks. Each different type of rocket engine may have to cope with different errors. Particularly, liquid rocket engines, despite being very efficient, rely on complex systems and components, such as turbo pumps and combustion chambers, which can lead to problems concerning overheating, instability and fuel system malfunctions.

As far as solid rocket engines are concerned, they are simpler and more reliable than most of the engines. Once they are ignited, they can never be throttled or shut down, making them susceptible to certain dangers, including explosions, loss of control and mission failure.

Combining aspects of both liquid and solid engines, hybrid engines use a liquid oxidizer and a solid fuel. In spite of their mechanical simplicity and their ability to be throttled down, their efficiency and thrust often are inadequate when compared to liquid engines, thus they can be challenging to manufacture. Furthermore, ion engines, though they are highly efficient, produce minimal thrust. Consequently, they require long operational periods, which increase the rocket's exposure to space radiation and the chances of an engine failure. Additionally, they demand an immense amount of electrical power, which is difficult to generate when taking into consideration the limited energy that is available on the aircraft.

Lastly, nuclear engines face challenges concerning the handling and safety of radioactive materials, especially during a rocket's launch failure. Identifying and addressing these failure modes is imperative for ensuring rocket engine improvement and the increase in successful space missions.

3.2 Sub-Theme: Structural Failures

Rocket structural failures are one of the greatest and most critical challenges in aerospace engineering, often leading to a mission failure or detrimental destruction. Such failures mostly occur when a rocket's framework cannot endure the extreme forces of launch, flight, and re-entry back on Earth, leading to catastrophic collapses, ruptures or breakups. Factors such as material weaknesses, design flaws, aerodynamic stress, and unexpected external conditions, can all play a part in structural breakdowns. Understanding these failures is essential for improving durability and increasing safety in space travel, thus improving the reliability of future space missions.

A recent example that underscores the utmost importance of addressing these challenges occurred during SpaceX's Starship test flight on January 16, 2025. Although the booster landed successfully, the spacecraft later experienced an unexpected and sudden breakup, resulting in its loss. Early investigations and analysis suggest that fuel leakage led to pressure building up in a cavity above the engine firewall, emphasizing the need for stronger structural integrity when constructing rockets. This event serves as an ongoing reminder of the complex hurdles and challenges engineers are called to face in ensuring the safety and reliability of rockets in space missions.

In conclusion, rocket structural failures are a key challenge in aerospace engineering, caused by factors, such as material flaws and design issues. The recent SpaceX test flight incident underscores the growing need for robust rocket structures. Overcoming these challenges is crucial for improving safety and dependability of future space missions.

3.3 Sub-Theme: Re-Entry Challenges

Re-entry into Earth's atmosphere presents one of the most demanding phases of space travel. As a rocket descends from space, it must undergo extremely high temperatures, and pressure, as well as rapid deceleration that is encountered throughout this phase. All of these make the rocket highly vulnerable to structural damage, or even complete failure. To overcome such challenges, all spacecraft must be equipped with up-to-date heat shields that can protect the rocket from extreme heat faced when re-entering. They must also be armed with durable materials that can withstand such conditions, but also precise navigation systems, so as to guarantee a safe return on the ground and to prevent any catastrophic and fatal damage. Engineers must work conscientiously and carefully when designing these systems to protect both the spacecraft and its occupants and to optimize the re-entry phase for successful landings.

In conclusion, spacecraft re-entry is a complex process that requires overcoming extreme temperatures, functioning at very high speeds, and withstanding intense pressures. The

advancements in re-entry technology continue to play a pivotal role in the success of space missions and the safety of astronauts.

3.4 Sub-Theme: Overcoming Key Challenges for Space Mission Success

Finally, rockets face numerous difficulties, from structural and engine failures, to withstanding extreme conditions during flight and re-entry. Overcoming these challenges is crucial for advancing space exploration, improving rocket reliability, and ensuring the safety of both the crew and equipment. Ongoing technological improvements, continuous testing and innovation will forever play a critical role in achieving greater success in the future of space travel.

Conclusion

Rockets have transformed space exploration, allowing humans to push beyond Earth's boundaries and uncover the deep secrets of the cosmos. However, their development comes with significant perplexities, from structural integrity and optimizing thrust and propulsion, to ensuring precise navigation and a safe re-entry back on the ground. Engineers continuously refine materials, designs and technology, in order to enhance performance and reliability. As advancements in materials, artificial intelligence and rocket designs surface, the future of rocketry promises even greater possibilities. With each breakthrough, space travel moves one step closer to becoming more accessible, sustainable and capable of taking humanity deeper into the cosmos.

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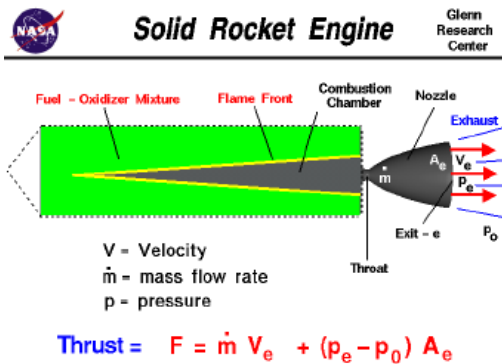
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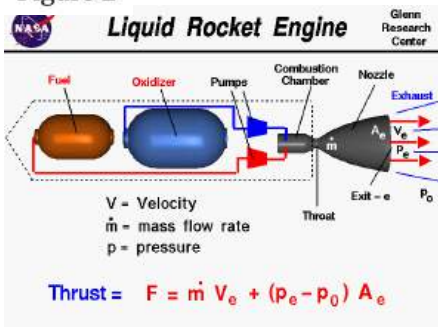
Tables and Figures

Figure 1

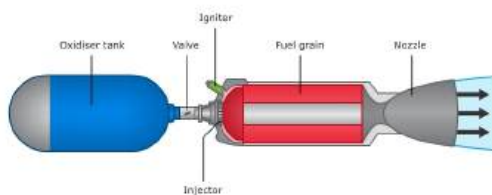


In this figure, the different parts of a solid rocket engine are shown. These are: the mixture of fuel and oxidizer, the combustion chamber and the nozzle.

Figure 2



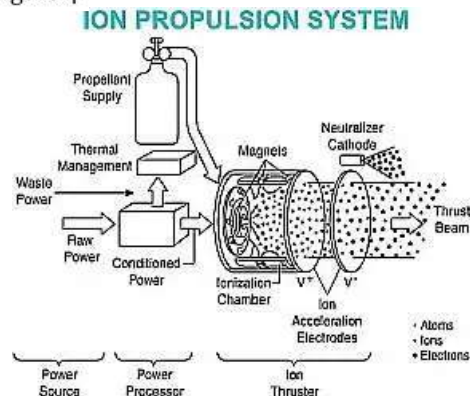
This figure shows the different parts of a liquid rocket engine. These include the oxidizer tank, the fuel tank, the combustion chamber, the nozzle and the pumps.



In this figure, the different parts of a hybrid engine are shown. These are: the oxidizer tank, the valve, the fuel grain, the igniter, the injector and the nozzle.

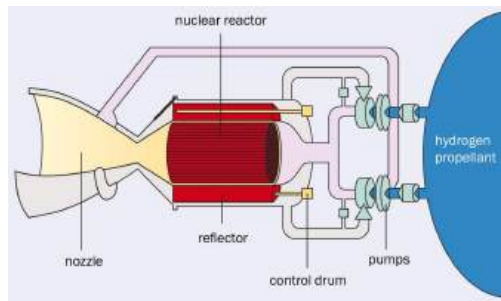
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Figure 4



In this figure, we can see the different and complex parts of an ion engine.

Figure 5



This figure highlights the basic parts of a nuclear engine.

Figure 6



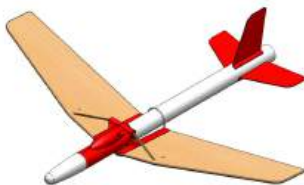
This figure shows the parachute landing method.

Figure 7



This figure shows the streamer landing method.

Figure 8



This figure shows the glider landing method.

Table 1

<i>Criteria</i>	<i>Why is this criterion important?</i>
a. Descent and Landing precision	A successful descent and landing depends on the rocket's ability to control its motion throughout descent.
b. System Reliability and coordination	Engines, structures, navigation, and landing systems must work together reliably under harsh and constantly changing conditions.
c. Engine performance during landing	Engines must reduce speed smoothly and steadily and adjust thrust to control descent without causing instability, thus preventing an unsuccessful landing.
d. Structural Strength	Rockets must be able to cope with extreme stress and impact during descent and landing without breaking or deforming.
e. Reusability	Reusable rockets save money and resources, but only if they can land safely and work again with minimal repairs.

In this table all the rockets mentioned above will be evaluated based on how much they adopt each of the criteria mentioned in the methods. A scale of 0-5 will be used with 5 being a criterion being fully adopted.

Table 2

Criteria	Rocket 1	Rocket 2	Rocket 3	Rocket 4	Rocket 5
a.	5	4	2	1	5
b.	5	3	4	4	5
c.	5	4	0	4	5
d.	4	4	5	5	4
e.	5	4	4	0	5

A Country's Development and Their Population's Attitudes Towards International Trade

By Napat Jiratunlathorn

Abstract

This article explores the relationship between national development levels and public attitudes toward international trade. While anecdotal evidence and previous research indicate that individuals with higher skill levels and educational attainment tend to be more supportive of international trade, it might be inferred that high-income countries—where such individuals represent a larger portion of the population—would exhibit generally more positive perspectives on trade. This study reviews academic scholarship concerning determinants of attitudes toward trade, supplemented by survey data from selected countries to support the findings in the literature. The results suggest that a clear positive correlation between trade optimism and a country's level of development is not always observed; in certain instances, populations in lower income countries display greater optimism. The analysis further indicates that, although many view international trade as advantageous for their country, they may perceive fewer direct personal benefits.

Introduction

International trade often generates varied reactions based on both economic and non-economic considerations. The importation of goods and services from foreign countries may provoke skepticism in some individuals, while others may find it intriguing.¹²¹ Regardless of differing opinions on international trade, its theoretical purpose is to foster national growth, promote economic development, increase employment opportunities, and enhance international relations.¹²²

The foundation of international trade lies in the concept of Comparative Advantage, whereby a country produces a specific good at a lower opportunity cost than other nations.

One significant theory that informs our understanding of free trade is the concept of 'comparative advantage,' introduced by political economist David Ricardo in his 1817 treatise, 'Principles of Political Economy and Taxation.' From 1815 to 1846, the United Kingdom enacted legislation limiting wheat imports in order to safeguard domestic agriculture. Ricardo advocated for an alternative approach, contending that nations should focus on producing goods and services for which they possess a comparative advantage while importing those for which they do not. This specialization, he argued, would ultimately enhance national prosperity.¹²³

For example, country A possesses a comparative advantage in automobile production relative to country B, whereas country B holds a comparative advantage in computer

¹²¹ Congressional Research Service, US Trade Debates: Select Disputes and Action, 9th August 2024, Page 1, Introduction, line 2-3

¹²² Hieu Huu Nguyen, "Impact of Foreign Direct Investment and International Trade on Economic Growth: Empirical Study in Vietnam", Page 331, Conclusion line 6-8, Journal of Asian Finance, Economics and Business Vol 7 No 3 (2020)

¹²³ Corporate Financial Institute: Comparative Advantage

manufacturing over country A. Consequently, each nation tends to specialize in its respective industry, enabling car manufacturers in country A and computer producers in country B to prosper through exports, thereby increasing profitability and fostering business growth. However, this specialization may also result in heightened unemployment within the car sector of country B and the computer sector of country A, as some workers face job displacement—though certain individuals may transition to new roles while others may rely on unemployment benefits. This dynamic underscores that international trade yields both advantages and disadvantages for different segments of the population. As such, many countries continue to debate key issues surrounding international trade, including whether to allow imports from neighboring nations, implement tariffs to protect domestic industries, or risk escalating into undesirable trade disputes.

Debates surrounding international trade are not limited to world leaders, government officials, and economists; members of the general public also express their perspectives and sentiments on the matter. This engagement may stem from an awareness of the potential consequences of international trade, regardless of their accuracy.¹²⁴

Whether it's 'People will lose their jobs.' or 'There could be spyware imported from another country'. The origin of some people's attitudes are due to economic factors, for example their education on international trade, their eeriness over the country's economy. Some research indicates that highly skilled and educated people are relatively more supportive of international trade, which may be because they are taught the benefits of free trade at university.¹²⁵ Or maybe because the less skilled and educated are more sensitive to political framing.¹²⁶ Developed countries have, in general, a larger number of quality higher-education institutions so it would make sense that they would have more university graduates and educated people as a proportion of their population. On the other hand, some people's attitudes are due to non-economic factors like their age, ethnicity¹²⁷ and gender¹²⁸. Both of the economic and non economic factors may have a causation or correlation to a country's development. Therefore, I want to explore whether this means the population in developed economies have a more open and positive attitude towards international trade.

The initial section of this paper presents a literature review aimed at identifying the prevailing perspectives on attitudes toward trade in both high- and low-income countries. The analysis reveals two primary drivers of behavior: economic factors (including skills, education, and economic interdependence) and non-economic factors (such as security and demographics). Subsequently, I evaluated the methodologies employed in the reviewed studies and observed that the majority utilized the PEW Global Attitudes Survey. Based on this, I selected three survey

¹²⁴ Shanay Gracia, "Majority of Americans take a dim view of increased trade with other countries", Pew Research Center, 29th July 2024

¹²⁵ Yannick Stiller, Andreas Dur and Robert A. Huber, "Education and Trade Attitudes: Revisiting and Role of Economic Interest", University of Salzburg, World Trade Review 2022

¹²⁶ Michael J. Hiscox, "Through a Glass and Darkly: Framing Effect and Individuals' Attitudes Toward International Trade", September 2003

¹²⁷ Diana C. Mutz, Edward D. Mansfield and Eunji Kim, "Effects of Race on Attitudes towards International Trade: Economics or Symbolic Politics?", University of Pennsylvania

¹²⁸ Brian A. Burgoon and Michael J. Hiscox, "The Mysterious Case of Female Protectionism: Gender Bias in Attitudes Towards International Trade", University of Amsterdam and University of Harvard, August 2004

questions from the same dataset, each addressing distinct aspects of attitudes towards trade—for example, whether respondents believed trade would benefit their country or themselves personally (e.g., potential wage increases). Finally, I conducted an empirical analysis comparing responses from high-income and low-income countries.

Literature review

The principal research component of this paper involves a comprehensive literature review aimed at identifying the determinants influencing public attitudes toward international trade. The selected studies examine various factors shaping whether a population expresses positive or negative perceptions of trade. This review spans disciplines such as economics and sociology and reveals two predominant schools of thought. The first school attributes public opinion primarily to socio-economic drivers, including economic interdependence, political dynamics, and educational attainment—with education considered an economic factor due to its correlation with overall economic performance. The second school highlights non-economic influences, such as cultural distinctions, psychological anxieties, prejudices, security considerations, and demographic variables like age and gender. Notably, these theoretical perspectives are not mutually exclusive; rather, scholars often acknowledge multiple contributing elements while underscoring the relative significance of particular determinants.

The initial perspective may be described as follows: economic factors serve as significant influences on a population's attitudes toward trade. Within this view, three key sub-factors can be identified: skills, education, and economic interdependence.

Yannick Stiller, Andreas Dur, and Robert A. Huber (2022) present compelling arguments regarding the significance of the 'Education' sub-factor. Their study addresses the ongoing debate concerning whether highly educated individuals demonstrate greater support for international trade. The authors test four hypotheses, concluding that the economic interest perspective maintains explanatory potential. Specifically, respondents residing in more developed and economically competitive regions, along with those who are employed and older, are more likely to perceive trade as having a substantial impact on jobs and wages compared to other groups. Overall, attitudes toward trade are shaped by an individual's perception of its consequences. Consequently, the study underscores the continuing relevance of economic interest in explaining these attitudes. Similarly, the paper "Import Competition and Public Attitudes towards Trade" (2021) by Alex Davenport, David Dorn, and Peter Levell is aligned with this sub-factor and further supports this perspective. To examine how public attitudes toward trade have evolved over time in developed countries and how they vary across population groups, the authors analyzed data from the Pew Global Attitudes Survey.¹²⁹ When asked if trade is good, the data showed that respondents who hold a university degree will be “more likely to believe trade is good”, in all countries. This could be because they are “less skeptical” on the impact of trade on “jobs, wages and prices”. This finding correlates with the one from Yannick Stiller et. al (2022). It is also

¹²⁹ Pew Global Attitudes Survey surveys different countries throughout decades and collects data from the results, asking them some repeating questions and some newer questions, based on many topics including international trade.

important to note that these responses are from different groups of people with different experiences. For example, lower skilled workers experience “more adverse” impacts of trade. Moreover, they may have “divergent views on the nature of trade’s benefits” and as a result “weigh these benefits differently”.

A closely related but distinct sub-factor to the initial category is "skills", which may be acquired through education but are not exclusively dependent upon it. The study by Michael J. Hiscox, entitled "Through a Glass and Darkly: Framing Effects and Individuals' Attitudes Towards International Trade" (2003), exemplifies this classification. Employing a survey experiment, Hiscox examined the influence of framing effects on participants' expressed attitudes toward international trade. The findings indicated that respondents exposed to an anti-trade frame were approximately 19 percent less likely to support increased international trade compared to those who received neutral framing. Conversely, exposure to pro-trade frames did not significantly alter the likelihood of expressing support for increased trade relative to the neutrally framed group. Furthermore, individuals with lower levels of education and skill were observed to be more susceptible to framing effects. Additional evidence is provided by Jakel and Smolka's work, "Individual Attitudes Towards Trade: Stolper-Samuelson Revisited" (2011), which investigates the extent to which individuals' preferences regarding trade policies align with the Stolper-Samuelson framework.¹³⁰ The results show that the “Heckscher-Ohlin-Samuelson model¹³¹” has a huge role in “explaining the formation of trade policy preferences”. Because the United States possesses many highly skilled workers, their “predicted probability of favoring free trade” increased. Their analysis suggests that if individuals have higher “economic awareness” they are more likely to be “open to international trade”. However, if they have “reservations against foreign cultures” they will be less open. This links to the non-economic current of thoughts. What production factors people are in are also important. An “integrated world economy”, which could mean interdependence, can affect scarcity of production factors, this can make people weary of trade. The implication here is that people are skeptical that trade may affect jobs and cause their unemployment, which corroborates with the findings of Alex Davenport et. al (2021).

The final sub-factor under consideration is “Economic Interdependence.” Kleinburg and Fordham’s 2010 work, “Trade and Foreign Policy Attitudes,” employs data from a forty-seven-country survey to examine how foreign policy attitudes are shaped by economic interdependence. Their findings indicate that individuals residing in countries more reliant on exports tend to hold less negative views of their trading partners. Conversely, the impact of imports generally remains inconclusive, except in the case of China, where increased import exposure is correlated with greater likelihood of unfavorable opinions towards China. In

¹³⁰ The Stolper-Samuelson logic or theorem: If production of one good increases due to specialization, demand for the factor of production used to produce that good will also increase. Increasing price of that factor and decreasing price of other factors of production. Showing that there are losers and winners in international trade.

¹³¹ The Heckscher-Ohlin-Samuelson model suggests that “if your country is relatively capital abundant then your country has a comparative advantage in the production of capital intensive goods.” And vice versa for countries with labor abundance.

summary, when a nation imports significantly more than it exports to a trading partner, the bilateral relationship may become susceptible to conflict.¹³²

Supporting this perspective, Braml and Felbermayr's 2018 paper, "Understanding Free Trade Attitudes: Evidence from Europe," highlights that public opinion about open-market policies is primarily influenced by ideological factors rather than purely rational or economic interests. The authors underscore the importance of institutional trust, and observe non-linearity regarding age, suggesting no consistent link between age and openness to trade. Echoing earlier findings, they note that higher import exposure tends to diminish support for open markets, whereas greater export exposure enhances it. These results align with the behavioral economics concept of loss aversion, which posits that potential losses are perceived as more significant than corresponding gains.

The second perspective asserts that non-economic factors exert significant influence on attitudes toward international trade. This approach encompasses two key dimensions: security and demographics.

Individuals may develop reservations about trade due to concerns related to job security or overall safety. For some, apprehensions arise from the substantial influx of foreign goods, which may be perceived as a threat to national security. In "Economics, Security and Individual-Level Preferences for Trade Agreements" (DiGiuseppe & Kleinberg, 2019), the authors investigate whether and under what circumstances security considerations affect individual attitudes toward trade. The study poses two central questions: first, to what extent do expectations regarding the security implications of trade impact individual attitudes toward trade agreements, and second, does raising security issues influence how individuals weigh the economic costs and benefits of such agreements? The findings indicate that security-related concerns can significantly affect attitudes toward trade, such as reduced support for trade agreements if global influence is perceived as diminished or if closer economic ties are established with potential political rivals. Moreover, the research demonstrates that individuals tend to balance gains and losses in interconnected areas, with loss aversion serving as a critical factor shaping their perspectives on trade.

The second sub-factor concerns demographics. Race and gender frequently influence how individuals are perceived and treated, which in turn can shape their perspectives. The study "Effects of Race on Attitudes toward International Trade: Economics or Symbolic Politics (2017)" by Diana C. Mutz, Edward D. Mansfield, and Eunji Kim highlights differences in attitudes toward international trade based on these factors. While minority status is often associated with characteristics such as lower skill levels, reduced earnings, higher rates of unemployment, and less economic education—factors that might suggest a greater hostility toward trade—the research reveals the contrary: minorities are significantly more supportive of international trade than whites.¹³³ This can be attributed to individuals' tendency to be younger,

¹³² It is the tendency to avoid losses over receiving equal wins. People view losing something as worse than receiving something of equal value. This is a part of the 'Prospect Theory' by Nobel Prize Winner Daniel Kahneman and Amos Tversky

¹³³ The research for this study was conducted in the United States

less nationalistic, and less prejudiced. Additionally, those who are less likely to reside in regions with a significant manufacturing base are noteworthy, particularly considering that the manufacturing sector in the United States has been adversely affected by trade. Similar to the impact of race, gender also shapes attitudes towards these issues. As highlighted in "The Mysterious Case of Female Protectionism: Gender Bias in Attitudes Towards International Trade (2004)" by Brian A. Burgoon and Michael J. Hiscox, conventional political economy models do not account for the differences in attitudes between males and females ¹³⁴, specifically how international trade affects income distribution and gender differences in jobs. Research indicates that, relative to men, women tend to exhibit less favorable attitudes toward the international economy. Notably, the study concludes that, when controlling for other variables, increased female participation or influence in politics correlates with higher equilibrium trade barriers. The authors also propose that gender-based differences in attitudes may stem from disparities in exposure to economic concepts and information among college-educated men and women, thereby influencing their perspectives on trade.

Authored by Sofia Vasilopoulou, Liisa Talving, and Daniel Keith, the study "Public attitudes towards international trade and free trade agreements in the United Kingdom (2024)" examines perspectives on international trade within the UK. The analysis finds that non-economic and contextual factors hold greater relevance than purely economic explanations in shaping public opinion. The research indicates that support for Free Trade Agreements (FTAs) and international trade is closely linked to a strong sense of national identity. Furthermore, when trading partners are seen as holding a stronger negotiating position, individuals tend to view FTAs as less advantageous. Notably, the authors highlight that the influence of identity is highly context-dependent, with elements such as partisanship and identity interrelated, particularly in the context of Brexit.

Methodology Review

The ten papers discussed provide insight into the factors and indicators influencing individual behavior in the context of trade. Upon analysis of this literature, my aim is to clarify the methodologies and data sources utilized by the respective authors, thereby offering a more transparent understanding of their evidence and findings. The majority of the reviewed works employed surveys to gauge both the direction and determinants underlying attitudes towards trade. The table below summarizes the surveys referenced by the papers highlighted in the preceding section.

Surveys used by papers examined in the literature review

¹³⁴ A framework about how economic and political factors can shape the distribution of resources and societal outcomes

Pew Global Attitudes Survey ¹³⁵	Eurobarometer Survey ¹³⁶	TESS ¹³⁷	Other Surveys
Kleinberg and Fordham (2010), they used the survey from Spring 2007 (47 countries)	Martin Braml and Gabriel Felbermayr (2018)	Michael J. Hiscox (2003)	Mutz, Mansfield and Kim (2021), used multiple pre-existing surveys
Davenport, Dorn and Levell (2021), they used surveys from OECD countries 2002-2018		Brian A. Burgoon and Michael J. Hiscox (2004)	DiGiuseppe and Kleinbergs (2019), designed their own survey
Jakel and Marcel (2011), they used the survey from 2007 (47 countries)			Vasilopoulou, Talving and Keith (2024), used two cross sectional surveys by YouGov (2019 and 2022)
Stiller, Dur and Huber (2022), they used the survey from Spring 2014 (36 countries)			

Fig 1: The table shows the summary of surveys used by the papers reviewed in the previous section

The predominant methodological approach among leading contributors to the literature in this field involves utilizing pre-existing surveys or developing original survey instruments.

Analysis

A review of multiple studies concerning trade and development indicates a broad consensus: countries with higher levels of development tend to hold more favorable views toward trade. To independently investigate this relationship, I sought to determine whether nations with greater economic advancement exhibit a more positive attitude towards trade. Analysis of methodologies from relevant literature revealed that four out of nine studies utilized data from the PEW Global Attitudes Survey, though these studies referenced different years and countries. For

¹³⁵ Pew Research Center is a “non-partisan fact tank”, they made the Pew Global Attitudes Project. Which is a “series of world wide public opinion surveys” that ranges from many countries across many years.

¹³⁶ The Eurobarometer is a “collection of cross-country public opinion surveys conducted regularly on behalf of EU institutions since 1974”, results are from “all EU member states and some additional countries and territories”

¹³⁷ TESS stands for Time-Sharing Experiment for the Social Sciences program, the survey conducted through TESS was “administered by telephone” from the “Center for Survey Research at Indiana University”

my own research, I selected three questions from the PEW Global Attitudes Survey administered between 2014 and 2018.¹³⁸

Questions from the PEW Global Attitudes Survey
1) Does trade with other countries lead to job creations in (survey country), job losses or does it not make a difference?
2) <i>What do you think about the growing trade and business ties between (survey country) and other countries - do you think it is a very good thing, somewhat good, somewhat bad or a very bad thing for our country?</i>
3) <i>Does trade with other countries lead to an increase in the wages of (survey country nationality) workers, a decrease in wages, or does it not make a difference? (2018)</i>

Fig 2: Questions chosen for analysis

I used the income and development classifications used by the World Bank¹³⁹ to specify the countries included in this analysis. The classifications applied are those utilized by both organizations to group countries according to income levels.¹⁴⁰ (High income, Upper middle income, Lower middle income and Low income).

The PEW Global Attitudes Survey posed the question: “Does trade with other countries lead to job creation in (survey country), job losses, or does it not make a difference?” in both 2014 and 2018, across the same countries. Findings indicate that in nineteen out of twenty-one countries, a majority of respondents viewed international trade as conducive to job creation (highlighted in green). Notably, the only two countries where ‘job loss’ was cited more frequently (highlighted in pink) were both high-income economies: the United States in 2014 and Australia in 2018. Countries with over twenty percent of responses falling under ‘No difference’ are highlighted in yellow; this perspective appears distributed relatively evenly among countries of varying development levels.

Overall, respondents around the world, irrespective of year, tend to associate international trade with job creation. It is important to highlight, however, that lower-middle and low-income countries report higher optimism regarding employment outcomes from trade compared to their high- and upper-middle-income counterparts. For instance, figures for the ‘Jobs created’ category

¹³⁸ Pew Global Attitudes and Trends Question Database, Pew Research Center, Washington, D.C (2008, 2014 and 2018)

¹³⁹ World Bank (2024) – with major processing by Our World in Data. “World Bank income groups” [dataset]. World Bank, “Income Classifications” [original data]. Retrieved February 22, 2025 from <https://ourworldindata.org/grapher/world-bank-income-groups>

¹⁴⁰ Since PEW did not ask these questions in every country, I had to further select from the list I had originally created the countries that were included in the PEW surveys. The income classifications are based on 2023 income. The Pew surveys were conducted between 2014 and 2018. Analyzing the represented countries’ gdp per capita, I verified that each country belonged to the same income classifications categories in the range of time examined. There was one single case of an older survey (Ethiopia 2007), but Ethiopia was still in the lower income countries group.

in lower-middle and low-income countries typically range from the 60s to 80s, with Egypt in 2014 as an exception, whereas high- and upper-middle-income nations generally fall within the 30s to 50s, except for China in 2014. This trend challenges the assumption that more developed countries possess greater positivity towards trade. In summary, averages by income category reveal that lower-middle and low-income nations exhibit a more optimistic outlook on the impact of trade on employment than higher-income countries. Nevertheless, the overall global sentiment towards trade remains broadly positive.

Countries	Jobs created	Job losses	No difference
High income			
US 2014	20	50	25
US 2018	36	34	24
UK 2014	50	19	24
UK 2018	49	17	29
South Korea 2014	53	19	24
South Korea 2018	57	22	18
Australia 2014	45	21	18
Australia 2018	19	53	19
Average	41.1	29.4	22.6
Upper middle			
Thailand 2014	43	24	26
Indonesia 2014	63	19	14
Indonesia 2018	52	22	20
China 2014	67	11	10
Mexico 2014	43	26	25
Mexico 2018	35	26	34
Brazil 2014	56	15	25
Brazil 2018	40	26	29
Average	49.9	21.1	22.9
Lower Middle			
Egypt 2014	49	23	21
Ghana 2014	62	18	15
Kenya 2014	75	15	9

Kenya 2018	66	18	14
Average	63	18.5	14.8
Low income			
Uganda 2014	82	12	4
Average	82	12	4

Fig 3: Table for the question ‘Does trade with other countries lead to job creations in (survey country), job losses or does it not make a difference?’ (percentage of total respondents in each category)

The second question asked by the PEW Global Attitudes Survey asked people in countries from the year 2014 and 2018¹⁴¹ if they think that growing trade between their countries and other countries is a good thing or not. The countries that have ‘somewhat good’ as their majority answer are highlighted in green, this is 12/16 country/year. The countries that answered ‘very good’ were UK 2018, Ghana 2014, Kenya 2018 and Uganda 2014. Because these countries vary from High to Low income, it is not apparent a correlation between the level of development of the country and the answer is ‘very good’. And highlighted in red are countries that have more than 20% in the somewhat bad column. All countries from every year answered ‘very good or somewhat good’, none had said growing trade and business ties between countries are ‘bad’. What this shows is that all the people surveyed from the countries here had a general idea of the benefits of trade, it may not have benefitted them personally, but their countries would no doubt be better off. All countries at all levels of income seem enthusiastic about the benefits of trade with other countries, so the overall level of support may not be completely correlated by income. However, the intensity of enthusiasm is much more pronounced in the Lower-middle and Low income countries, as seen in the average scores.

Countries	very good	somewhat good	somewhat bad	very bad
High income				
US 2018	31	43	14	7
UK 2018	50	39	6	2
South Korea 2018	38	54	5	1
Australia 2008	35	51	10	2
Australia 2018	36	51	8	2
Average	38	47.6	8.6	2.8

¹⁴¹ With the exception of Ethiopia 2007 and Australia 2008

Upper middle				
Thailand 2014	20	47	23	6
Indonesia 2018	42	44	8	2
China 2014	24	65	4	1
Mexico 2018	30	49	10	9
Brazil 2018	18	54	16	7
Average	26.8	51.8	12.2	5
Lower Middle				
Egypt 2014	26	44	20	10
Ghana 2014	42	33	10	11
Kenya 2018	68	22	5	5
Average	45.3	33	11.7	8.67
Low income				
Ethiopia 2007 (non national)	32	54	8	1
Uganda 2014	70	20	5	4
Average	51	37	6.5	2.5

Fig 4: Table for the question ‘What do you think about the growing trade and business ties between (survey country) and other countries - do you think it is a very good thing, somewhat good, somewhat bad or a very bad thing for our country?’ (percentage of total respondents in each category)

Regarding the third and final question, the data indicate that individuals across high, middle, and low-income nations commonly perceive international trade as having no impact on their wages. In five out of nine countries, a plurality responded that trading with other nations would make 'no difference' to wage levels, either positively or negatively. Notably, one country from each income group—South Korea, Indonesia, and Kenya—showed a majority opinion that increased trade would lead to higher wages. The United States stands out as the only country surveyed where respondents were equally divided among all three options, reflecting a split in perspectives on trade’s impact on wages. Furthermore, the table reveals greater variability in opinions, particularly among high-income countries. A substantial portion of participants in more

than half of the surveyed nations expressed uncertainty about trade affecting their wage levels, suggesting widespread ambivalence regarding its personal impact.

Countries	Increase	Decrease	No difference
High income			
US	31	31	30
UK	34	15	43
South Korea	56	18	22
Australia	27	29	36
Average	37	23.3	32.8
Upper middle			
Indonesia	47	26	21
Mexico	27	21	48
Brazil	32	20	41
Average	35.3	22.3	36.7
Lower Middle			
Philippines	42	8	49
Kenya	61	18	18
Average	51.5	13	33.5

Fig 5: Table for the question ‘Does trade with other countries lead to an increase in the wages of (survey country nationality) workers, a decrease in wages, or does it not make a difference?’ (2018) (percentage of total respondents in each category)

Analysis of responses to Q2 (*What do you think about the growing trade and business ties between (survey country) and other countries - do you think it is a very good thing, somewhat good, somewhat bad or a very bad thing for our country?*) indicates that, across all surveyed nations and income levels, the majority of respondents perceive international trade as beneficial to their country. This question’s design enables inference regarding the general view of trade’s impact on national economies. In contrast, Q1 (*Does trade with other countries lead to job creation in (survey country), job losses, or does it not make a difference?*) and Q3 (*Does trade with other countries lead to an increase in wages for (survey country nationality) workers, a decrease in wages, or does it not make a difference? 2018*) assess perceived effects at the individual level. Generally, the sentiment reflected in Q2 is more favorable toward international trade than the attitudes expressed in Q1 and Q3, where specific impacts on employment and

wages are considered; while still positive, these views are comparatively tempered. The findings suggest that, although populations believe trade is advantageous for their nation overall, there is less confidence in its direct benefit to individuals.

Conclusions

The literature review reveals a prevalent theme: countries with higher levels of development typically exhibit more positive attitudes toward international trade. The body of literature in this area can be categorized into two principal schools of thought. One posits that economic factors primarily determine these attitudes, while the other contends that cultural, demographic, or ideological elements are more influential. Both perspectives generally suggest that developed nations tend to favor international trade more than developing nations. However, this pattern is not consistently evident when examining individual responses to trade-related questions from the Pew Global Attitudes Survey. My analysis indicates that a country's income level does not significantly affect whether its population holds favorable or unfavorable views on international trade. Overall, respondents express optimism about trade. Variations in responses across different survey questions suggest that individuals are capable of recognizing both the benefits and drawbacks of international trade and distinguishing between its personal impact and its effects on the broader economy. These insights may help explain why public opinion on trade is often nuanced and may appear inconsistent.

This paper set out to identify and synthesize the principal literature regarding global attitudes towards trade, delineate prevailing schools of thought, and assess the validity of these findings through analysis of the widely utilized Pew Global Attitudes Survey. Prior research substantiates several determinants of attitudes towards international trade, yet further investigation demonstrates that no definitive conclusion emerges. This observation suggests the existence of additional, unexplored factors influencing public attitudes, particularly given marked fluctuations in opinions within individual countries.

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A Comparative analysis of Menu Format on Consumer Decision Making

By Swara Patel

Abstract

The digital transformation in the restaurant industry has significantly accelerated in the past decade, and digital menus are emerging increasingly in almost every restaurant in India. With this change in the menu format, the decision making of consumers is heavily impacted, especially with the abundance of choices, which can often lead to decision paralysis and choice overload. This research study investigates the impact of menu format (digital vs physical) on the decision making of consumers. The study is done using the t-test analysis of the responses of the 22 participants of a survey conducted to measure the decision paralysis, choice overload, decision making time, and post-decision satisfaction caused by a physical menu as compared to a digital menu. The findings suggest that consumers face a greater decision-making dilemma when ordering from a digital (QR code) menu, indicated by higher decision paralysis and choice overload experienced with digital menu than with a physical menu. The study has implications for the food and beverage industry for understanding user experience and consumer behaviour.

Keywords

Decision paralysis, Physical Menu, Restaurants, Digital Menu and Consumer Behaviour.

Introduction

Menus in the food industry hold a significant role in the success of a restaurant. It is more than just a list of food and beverages offered by the restaurant; it is a form of communication between the restaurant and customers that requires planning, designing, and detailing (Ozdemir, Bahattin, and Caliskan). It is a vital part of the entire dining experience and affects the customer satisfaction and their perception of the restaurant (Jawabreh et al.). A menu is what helps the customer create an expectation of the food and beverages they order, and builds the value and quality of the restaurant in the customer's mind. A significant impact of menu design was found on customer satisfaction. In menu design, placement of items in a proper sequence, and the diversity in design has the most effect on the customer satisfaction (Jawabreh et al.).

In recent years, the demand for consistent, technology-based experiences has risen, causing the hospitality industry, especially the food service industry to observe a digital transformation. The physical menus soon transformed to digital menus provided by restaurants through QR codes, websites, and mobile apps. It has proven to be a useful tool that has reshaped the dining experience (Gurbangeldiyev and Gavirova). This change significantly accelerated during the COVID-19 pandemic, and led to many restaurants in India adopting digital menus. A study carried out to understand the benefits and challenges of a QR code menu found that a majority of restaurants have embraced the incorporation of digital menus, while a few interviews conducted in the study suggested that some restaurants adopted digital menus only due the regulatory requirements which made the use of contactless menus mandatory during the global

pandemic (Öztürk, Betül, and Ula.). Another study with a sample size of 129 respondents, reported that despite the increased adoption of digital menus because of their flexibility and technological superiority, a significant number of customers (44.7%) still prefer the traditional physical menus, primarily because of their ease of use. The study reveals that the majority of restaurants today offer both digital and physical menus to suit different customer demands, which signifies the need for a hybrid solution for the highest overall customer satisfaction (Oktavia and Tanty).

A physical menu often evokes the feeling of nostalgia and familiarity, while digital menus are appreciated for convenience and interactive features (Surekha and Ali). The process of ordering food is affected by this difference in menu formats, often leading to customer dissatisfaction due to ordering an item they didn't actually enjoy. A study suggests that the decision paralysis effect can have an impact on the consumer purchase decision because they experience a dilemma due to the many food choices offered by the service providers (Viknesh, Gowda, and Banerjee). Too many options increase the complexity of the evaluation process and typically lead to a longer decision making process. Customers will think too much and struggle to make a decision, especially where most of the options are similar or the menu presentation is chaotic. Having a greater number of options doesn't always mean more satisfaction. Extensive lists of choices decrease satisfaction due to post-decision regret and the worry that there could have been a better one. Consumers exposed to a wide range of options are certain to be less satisfied with their final option, and satisfaction will be lower when the choice made was perceived not to be the best (Adriatico et al.). One of the strongest examples provided in the study is the "jam study," in which customers presented with 24 varieties of jam were significantly less likely to purchase than those presented with only 6. This confirms that menus with less options or shorter product descriptions can enhance satisfaction, reduce anxiety, and enhance decision speed (Adriatico et al.). Thus, while physical and digital menus offer convenience to customers and opportunity to restaurants to display their range of dishes, the format of the menu may also lead to choice overload and decision paralysis while ordering food.

While the existing literature has substantial research on digital transformation in the hospitality industry, consumer psychology in menu design, comparative analysis between physical and digital menus, and studies on decision paralysis and choice overload individually, the collective effect of it on the cognitive processes—how digital and physical menus change the way consumers think and make decisions—in Indian context has is less explored. Hence, to understand the impact of menu format on the decision making processes of consumers, this study explores said impact in terms of the decision paralysis and choice overload experienced by the consumers in Ahmedabad, Gujarat, India.

Methodology

Research Aim

This study aims to investigate the impact of menu format (digital vs physical) on the decision making of customers. The research adopts a quantitative approach, wherein a survey was carried out in restaurants in Ahmedabad, India. The objective of the study is to understand the effects of menu format on the decision paralysis and choice overload in consumers at a restaurant. This can help restaurants gain insight on the consumers' perspective, thus helping them understand the menu preferences of their clientele.

Tools used

The survey for the present study was divided into seven sections: menu format, demographics, menu experience, decision paralysis, choice overload, decision taking time post decision satisfaction. For the menu format, participants were asked whether they ordered from a physical menu or a digital menu; their general preference for the menu format was also recorded. The options included: physical menus, digital menus (via phone or QR code), no preference. In the demographics section, the participant's age, gender, occupation, and qualifications was collected to understand the profile of the sample. Following this, participants indicated how easy the menu format was to read, navigate, and understand by choosing from: easy, medium, hard. The participants continued with 'yes/no/maybe' responses for the next few questions like 'The layout of the menu was visually appealing.' For the following questions, the respondents were asked to indicate their level of agreement through the likert scale, where they selected 1 for 'Strongly Disagree', 2 for 'Disagree', 3 for 'Neutral', 4 for 'Agree', and 5 for 'Strongly Agree'. The decision paralysis (anticipated regret) (Oliver et al; Tsiros, Michael, and Mittal) section, measured their experience using statements such as fear of overlooking superior options, curiosity about alternative choices, concerns about others' expectations, where they rated their agreement to the statements using the likert scale. The next section—choice overload (Sprotles, George, and Kendall) followed the same format, where participants indicated their level of agreement for statements about confusion caused by too many items, difficulty in comparing items, and difficulty in obtaining an overview. The decision taking time (Heitmann, Mark, Lehmann, and Herrmann) section consisted of statements regarding the participants' perception of their decision-making time, and if they felt rushed. The last section, which is the post decision satisfaction (Fitzsimons, Gavan, Eric, Greenleaf, and Lehmann; Zhang, Shi, and Fitzsimons), used the same format to measure the participants' frustration levels, satisfaction with the variety of choice, willingness to order from the same set of choices, and overall interest in the decision-making process. The questions used for the Likert scale were taken from (Heitmann, Mark, Lehmann, and Herrmann). The data collection tool used was an online questionnaire made using Google Forms to efficiently gather responses from a sample of restaurant customers.

Data Collection

The data was collected in a restaurant in Ahmedabad, Gujarat. The restaurant managers were asked to first distribute digital and physical menus to different sets of customers. Then they were instructed to give a printed QR code to the customers—which, upon scanning, would open

the Google form containing the questionnaire—at the end of their meal. The customers would then proceed to fill out the questionnaire based on the menu they'd received and ordered from.

Ethical Considerations

Informed consent was obtained from all participants of the study prior to the start of the data collection. This is done by providing a brief explanation of the study and its purpose at the beginning of the Google Form survey. The participation was completely voluntary as they agreed to be a part of the study by answering the questions of the survey. The participants were allowed to withdraw at any time before submitting the survey with no penalties or consequences if they chose not to participate or to withdraw. They were ensured that their responses would be kept anonymous and strictly confidential. No identifying information such as their name or email address was collected unless explicitly stated. The data would be used for research purposes only and stored securely.

Sample Characteristics

A total of 22 responses were collected through the survey, out of this 11 ordered food through a digital menu and 11 ordered food through a physical menu (figure 1). The sample consisted of 45.5% of people aged 31-50, 31.8% of people aged 16-20, 18.2% of people aged 21-30, and 4.5% people aged above 50. Out of the 22 respondents, 14 were male and 8 were female. The participants' occupations ranged from 36.4% being students, 31.8% being business owners, 18.2% being in service, and the remaining 13.5% were equally distributed between a homemaker, a government employee, and a freelancer. Additionally, 54.6% of the participants were equally distributed between having the education qualifications of secondary school/high school, and a postgraduate degree, 31.8% had an undergraduate degree, while 9.1% of the participants had a Doctorate degree, and the remaining 4.5% had a diploma. All the participants indicated to be living in Gujarat, India; with 20 out of 22 being concentrated in Ahmedabad, Gujarat.

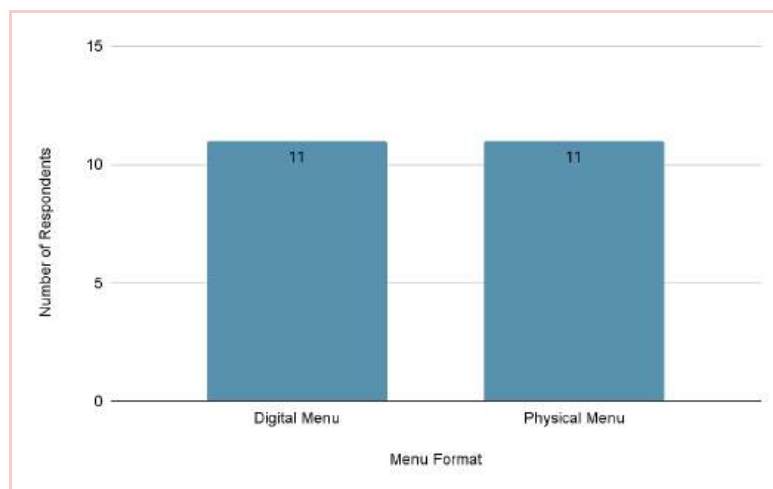


Figure 1: Graphical Representation of food ordered from different menu formats (N=22)

Data Analysis Procedure

The analysis for the study is a combination of descriptive and inferential statistics. Graphical analysis i.e. bar charts were carried out to depict the preference for menu format and to represent the number of participants who ordered from two different formats. Further, to test the group differences, an independent t-test was carried out through XLMiner Analysis Toolpak extension in Google Sheets. This was done to understand whether ordering from a specific kind of menu format leads to decision paralysis, choice overload, leads to longer decision taking time and post decision satisfaction.

Results and Discussion

This section reports the findings of the survey, examining the impact of menu format (physical/digital) on the decision making of consumers at restaurants. It is examined through four dimensions: decision paralysis, choice overload, decision making time, and post decision satisfaction. The results are presented using descriptive statistics and have been visually represented through graphs.

It was found that over 68% of the participants found the menu easy to read and understand, and over 81% found it easy to navigate. Additionally, 72.7% agreed that the menu had exhaustive options available, and 59.1% found the layout visually appealing.

Figure 1 below represents the preference of menu format for the sample. The graph shows that the majority of the sample i.e. 63.6% prefer physical menus for ordering food in restaurants in comparison to online menus. Similar findings were found by Hewage and colleagues, the findings suggest that “while QR code menus offer advantages in terms of contactless interactions and cost savings for restaurants, they are perceived as inconvenient in comparison to traditional printed menus,” (Hewage, Boman, and Lefebvre)

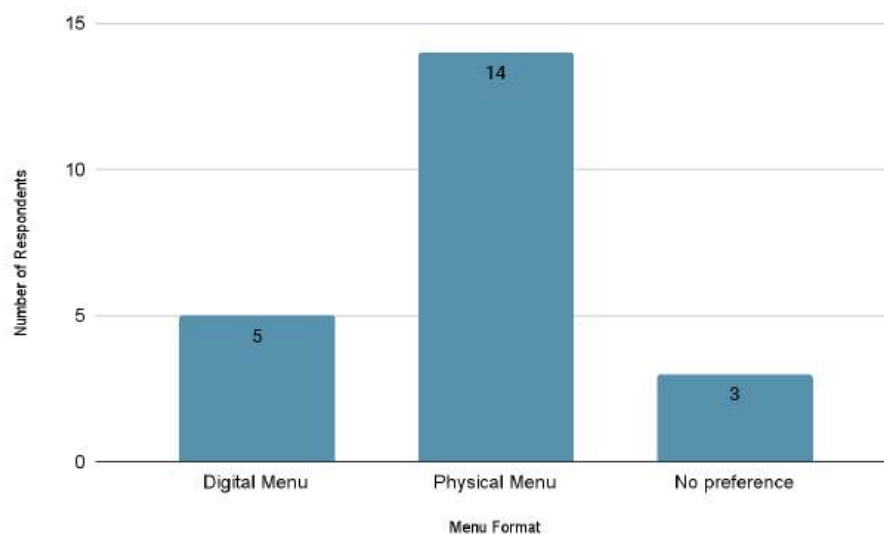


Figure 2: Graphical Representation of Preference for the Menu Format (N=22)

Table 1: Independent t-test analysis of sub-scales (Decision Paralysis, Choice overload, Decision Making Time, Post Decision Satisfaction) based on menu format (N=22)

Variable	Categories	N	Mean	SD	t	p value
Decision Paralysis	Digital Menu	22	11.36	4.01	1.56	0.06
	Physical Menu	22	8.36	4.97		
Choice Overload	Digital Menu	22	16.81	4.58	1.88	0.03*
	Physical Menu	22	12.45	6.19		
Decision making Time	Digital Menu	22	8.72	2.28	0.14	0.44
	Physical Menu	22	8.54	3.75		
Post decision Satisfaction	Digital Menu	22	20.36	3.33	-0.71	0.24
	Physical Menu	22	21.91	6.46		

*p<0.05

Table 1 depicts the differences between the decision paralysis, choice overload, decision making time, and post decision satisfaction among respondents who ordered food in a restaurant through a physical or a digital food menu. The t-test analysis shows that the respondents who ordered through a digital format experienced greater decision paralysis at (M=11.36, SD=4.01) than respondents who ordered from a physical menu (M=8.36, SD=4.965) given that $t(19)=1.56$ and $p=0.06$. Similarly, a higher choice overload was observed in respondents who ordered via a digital menu at (M=16.81, SD=4.58) than the physical menu at (M=12.45, SD=6.19) given $t(18)=1.88$ and $p=0.03$. The decision making time was higher when ordering from the digital menu indicated by (M=8.72) than for the physical menu (M=8.54). The post decision satisfaction after ordering from a digital menu is lower, indicated by (M=20.36), than after ordering from a physical menu (M=21.91).

These results suggest that there is an impact of menu format on the decision making of consumers, specifically, consumers are seen to be experiencing higher decision paralysis and choice overload when using a digital menu, while ordering from a physical menu causes lower decision paralysis paired with a higher post decision satisfaction. Similar results were obtained in the research by (Kaur) that indicate that the digital transformation has led to an abundance of information which has caused significant changes in the decision making and consumer choices

(Kaur). This can be applied to the digital transformation in menus and how it has caused greater decision making dilemmas in consumers compared to the physical menus.

This research study benefits multiple stakeholders in the hospitality industry. The stakeholders include restaurant owners and managers seeking to optimize menu design and format for higher customer satisfaction and revenue. Consumers can also gain a deeper insight on how menu format influences their decision making. Moreover, the findings may be beneficial to digital platform designers aiming to lower the decision paralysis and improve user experience in food ordering systems. The research holds the practical implications of navigating a balance between technological adoption and customer experience and satisfaction in the restaurant industry. The limitations of this research include having a small sample size for the study. Thus, the research holds lower statistical power, as there is a higher risk of a Type II error. Additionally, the sample consists only of people living in Gujarat India, which may reduce the generalizability of the findings. A larger, more diverse sample would allow greater reliability of results with greater statistical power.

Conclusion

This research represents the impact of menu format on the decision making of consumers, mainly focusing on the decision paralysis and choice overload caused by a physical menu as compared to a digital menu. The study suggests that higher decision paralysis and choice overload is experienced when ordering from a digital menu. It may prove beneficial to the hospitality industry, specifically the restaurant industry, that aims to improve customer experience and satisfaction through menu design and format. These findings should be employed with caution, given the limitations of having a small sample size for the study. Future studies can use a greater sample size to improve generalizability of the findings, so that it can represent a larger population. They can include cross-cultural comparisons to generate results for people of different age, gender, and income levels. Potential research can also look at the business metrics of restaurants to evaluate whether menu formats can influence sales and revenue.

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Bystander Effect and the Influence of Conformity By Moran Wang

Abstract

When figuring out if someone seemingly needs help, bystanders passing by will consider situational factors and interpersonal factors to figure out whether they decide to help. What is worth mentioning is that in most of the cases, they prefer to all pass by without giving help, and the probability of providing help is inversely proportionate to the number of bystanders. This research paper attempts to find out why most bystanders prefer to conform their beliefs about whether to help. Additionally, it explores how complex factors influence people's final decisions about whether to help. By using the Degroot model, the paper derives a math model to find out the formulas for bystanders' propensity to act by considering bystanders' assessment of situational factors and the proportion of the influence of these factors on their decision-making. It also used the trust matrix to represent the proportion of people's perception of the influence of others on themselves. After that, it used this as a basis to gauge the changes in people's beliefs after observing others' ones. Finally, it used quantitative data, propensity to act, and final belief to calculate the probability of their final choices to help to determine whether people eventually will help. The mathematical model concludes that most bystanders conform in their final decisions; however, some may deviate due to differences in their individual propensity to act. Specifically, bystanders with an extremely strong propensity to act, or groups with particularly low or highly updated beliefs, are more likely to break away from the majority and firmly choose their course of action. In contrast, others conform their behaviors based on environmental conditions and social influences. In this way, it helps people understand how bystanders make their decisions from a mathematical perspective, which simplifies complex situations in real life and makes precise, quantitative analysis.

Keywords: bystander effect, conformity, math model, the Degroot model.

Research Question

How does conformity influence bystanders' beliefs and how situational factors and interpersonal factors influence bystanders' decisions thereby causing a bystander effect?

Introduction

Nowadays, bystanders may always see others lying on the ground seemingly needing help. When facing this circumstance, what will they do? Having some emergency, will they just go away? Or will they believe the person is just pretending? Or, seeing no one else helping, will they also give up on the idea of helping? By considering various kinds of factors, most bystanders prefer to just pass by without helping. However, in some cases, when seeing someone start to help others, they begin to provide help too (Udochi Emeghara, 2023). And this is a famous phenomenon—the bystander effect. It is surprising that bystanders not only prefer to ignore the victim most of the time, but also conform their decisions about whether to

help or not.

However, a large number of early studies by scholars such as Darley & Latane mostly failed to precisely depict how the related psychological processes interact and ultimately drive the formation of decisions (Udochi Emeghara, 2023). At the same time, many theories often overlook a key fact: even in the same situation, there will still be individuals who choose to step forward. As for the reasons for the existence of such individual differences, traditional research has always struggled to provide a systematic explanation. In view of this, the mathematical model to be introduced below can not only solve the above problems but also provide quantitative and testable predictions.

This essay explores the causes of the bystander effect and its connection to conformity. In the section on the mathematical model, along with the included examples, the DeGroot model serves as a reference. Specifically, a mathematical model is constructed by identifying the relationships between three key elements: bystanders' initial beliefs (represented via a trust matrix), their updated beliefs, and their propensity to act (calculated using a specific formula). The latter parts of the essay provide a detailed explanation of how this model accounts for real-life scenarios, as well as an overview of some of the model's limitations. Since complex social phenomena often have underlying patterns that aren't immediately obvious, mathematical models provide a precise and objective language and allow for testable predictions.

Conclusively, this model is like an auxiliary learning tool, helping everyone better understand the specific process of the bystander effect and its relationship with conformity. There are also many advantages to using this model. Through quantitative data, this ambiguous and hard-to-define phenomenon in life can be represented by mathematical symbols and formulas. These quantitative mathematical symbols, which greatly represent the rigorous logic of mathematics, can also provide an alternative perspective to validate the bystander effect.

Literature Review

Bystander Effect

The bystander effect is a very well-known social psychological phenomenon. According to Latané and Darley, when others are present, an individual is less likely to offer help to the victim. Additionally, the probability of assistance is inversely proportional to the number of bystanders (Udochi Emeghara, 2023).

The decision-making process of an onlooker is not simple. Latané and Darley have proposed that before bystanders intervene in an emergency, they must go through a five-step cognitive and behavioral process (Udochi Emeghara, 2023):

1. pay attention to the event
2. interpret this event as an emergency
3. assume the responsibility of providing assistance
4. know how to help or have the ability to help
5. consciously make the decision to provide assistance. (Udochi Emeghara, 2023)

They also find out that the bystander effect is mainly caused by the failure of steps 2 and 3, and the presence of others creates the psychological impetus that disrupts this decision-making chain.

There are several key factors influencing the strength of the bystander effect. First of all, the diffusion of responsibility is a major factor. The responsibility to help is shared by all those present, thus distributing the burden of any one person (Kendra Cherry, 2025). In this way, when having multiple bystanders, their probability of providing help decreases, as each of them receives fewer responsibilities. Thus, they feel that they have less obligation to take action and just pass by. Secondly, pluralistic ignorance plays a key role. Bystanders observe the reactions of others in ambiguous situations to determine if there is an emergency. If others display calmness without taking actions, everyone interprets this situation as non-emergency, resulting in collective inaction (Kendra Cherry, 2025).

Furthermore, fear of evaluation can prevent intervention. Bystanders may hesitate to take action because they are afraid that they have misunderstood the situation, appeared stupid, or performed poorly in front of others (Britannica, Robert D. Blagg). When there are other bystanders present, the cost of assistance will also be measured more heavily. Thus, from this perspective, bystanders are less likely to provide help, since they don't want to increase the probability of making a fool of themselves and magnify what they have done.

However, this influence is not absolute and can be mitigated through specific factors. Research shows that if an emergency is clear and explicit, bystanders are more likely to offer help, as this reduces the need for social comparison. Furthermore, if bystanders feel a personal connection with the victim or are capable of providing assistance, such as having received first aid training, they are more likely to overcome the inhibitory effect of the group (Udochi Emeghara, 2023). These show that understanding the bystander effect itself can make individuals more vigilant and more likely to take responsibility in emergency situations.

In conclusion, the bystander effect is a powerful phenomenon rooted in the social and cognitive processes of responsibility diffusion, social influence, and evaluation understanding. Thus, understanding the sequential decision model and the factors that inhibit and promote helping behavior is crucial for increasing helping chances. These enable bystanders to overcome this inhibitory effect and become proactive helpers.

Conformity and Conformity Model

For a long time, the traditional social conformity model has been based on the principle that individuals tend to follow the average or average characteristics within a group. This framework effectively describes the scenarios in the most common feature sets, such as the distribution of working hours or food portions. However, when public opinion is bimodal or multi-modal, its applicability becomes invalid. For instance, in the political sphere, people may gather in places of extreme left and extreme right. The mathematical average—falling in the middle—is a poor and unrealistic indicator of popular characteristics (Institute, 2025).

To address this crucial gap, a new model was developed that exceeded the average and incorporated the concept of feature clustering. In this well-developed framework, the mechanism of conformity is redefined. Individuals adopt more universal and aggregated characteristics rather than developing towards the average level of the entire population. On the contrary, the model introduced anti-conformists who actively distanced themselves from the dominant group of their peers, thereby promoting polarization. Computer simulations of this model have revealed different results. That is, conformity leads to the formation of stable clusters around specific features, while anti-conformity produces a distinct U-shaped distribution characterized by extremely dense clusters and a blank center (Conformity, anticonformity and polarization of opinions).

A major discovery that challenges traditional wisdom is that, unless it is assumed that there is a perfect behavioral replication, populations rarely (if ever) tend to converge to a single, homogeneous feature, according to Kaleda Denton with colleagues. On the contrary, the model indicates that even minor changes in how individuals perceive and adopt features are sufficient to maintain continuous diversity within the population. This leads to a crucial conclusion: conformity is not necessarily a force of homogenization. Under certain conditions, it can actively maintain cultural differences, while anti-conformity systematically amplifies polarization (Institute, 2025). As researchers have pointed out, these results provide a more accurate consistency with real-world observations, where cultural customs and ideologies resist the average and instead maintain their unique cluster variations.

The Degroot Model

After exploring the nuances of conformity and its model, let's now turn to the Degroot Model. This model will allow us to delve into how network structure shapes influence dynamics and the evolution of beliefs, offering a complementary perspective on social interaction and opinion formation. Specifically, it studies how network structure determines people's influence dynamics and belief evolution (Lecture 5: DeGroot Learning Model).

The strength of this model lies in its abstraction of complex social behaviors into an easy-to-handle linear algebraic process. It assumes that each agent works through a simple, short-sighted heuristic: taking a weighted average of the current beliefs of their neighbors. This trust-based average mechanism directly captures the view that individuals are disproportionately influenced by those they are connected to and those they consider trustworthy. The relative weights of the network structure and influence are encoded into a random row trust matrix T , where each entry quantifies the direct impact of agent j on the formation of agent i 's beliefs.

The core analytical contribution of this model lies in establishing the conditions under which this mutually influencing iterative process leads to stable and long-term results. The proof of convergence utilizes the properties of the trust matrix as the transition matrix of the Markov chain. This model demonstrates that under standard connectivity conditions, the belief update process is a guarantee of convergence.

The convergence results have profound significance for understanding the dynamics of

collective opinions. This model proves that the system is not only stable; it reaches a homogeneous consensus that every individual in the network holds exactly the same beliefs. This final consensus value is not an arbitrary number but is precisely determined by the architecture of the network. It is the weighted average of all initial beliefs, where the weights are determined by the centrality of the agent in the influence network—effectively quantifying their ability to influence the opinions of the entire group as a function of their position and the trust others have in them (Lecture 5: DeGroot Learning Model).

What is worth mentioning is that this Degroot model is a general case, indicating that it does not have a strongly connected social network to have convergent beliefs. Accordingly, the idea that beliefs should be equally accessible or shared is generally not true in most cases. (Wikimedia, 2025) However, some researchers made improvements to the original version to fill the gap. For a revised version of the Degroot model, the DeGroot-Non-Consensus model indicated that non-consensus states occupy the largest portion of the parameter space, while consensus states are confined to a limited area. Additionally, it found that for small population sizes, neutral populations with high opinion variance exhibit robustness against fluctuations caused by the finite size of the population.(Qian, Han, Yang, 2024)

In conclusion, the DeGroot model provides an important theoretical benchmark. It demonstrates a simple and intuitive rule of social learning experience that is sufficient to enable a group to reach a consensus. This model ingeniously combines network topology with social psychology. This indicates that the pathways to consensus and the value of consensus are entirely determined by the underlying structure influencing weights, thereby reaching a state where no individual has the motivation to further modify their beliefs.

Methods

I began by reviewing available papers from Google and watching relevant videos on YouTube and applied insights from my psychology courses to develop an initial hypothesis. To deepen my understanding, I then explored existing literature on mathematical models, focusing on their principles and applications. During this process, I came across the DeGroot model, which I identified as a suitable framework for my research. Subsequently, I adapted this model to explain why bystanders' beliefs tend to conform and to elucidate the cognitive processes through which individuals integrate situational and interpersonal factors when making decisions. My next step was to examine whether the mathematical model could effectively explain or predict the bystander phenomenon. Finally, I refined the model to align more closely with the empirical details of the bystander effect, resulting in its final version.

Math Model

The following math model uses formulas to calculate bystanders' updated beliefs and their propensity to act, thus finding out their final decisions. It helps illustrate the bystander effect and its connection with conformity.

Let's take a community with one person lying on the ground seemingly needing help and

others surrounding this person. Assuming that n bystanders see this circumstance and each of them has a belief about this event, represented by a vector of probabilities $p(0)=(p_1(0),...,p_n(0))$.

This belief is an individual's subjective judgment and probabilistic cognition regarding the event of "someone falling to the ground in need of help". The following factors will influence bystanders' initial beliefs:

1. the victim who fell to the ground really needs help or this is a prank
2. the bystander has the responsibility to offer help
3. other bystanders will act first, so providing help is unnecessary
4. fear of evaluation on bystanders

(Britannica, Robert D. Blagg)

Additionally, bystanders' propensity to act takes into account situational and interpersonal factors without the intervention of others. They take into consideration:

5. whether the victim is similar to the bystander
6. whether the bystander stays in a remote area where fewer people prefer to enter
7. whether the bystander is in a hurry
8. whether the bystander and the victim know each other

(Udochi Emeghara, 2023)

Let's assume:

b: bystanders' thoughts about the weight of factor 5 that they think of.

c: bystanders' thoughts about the weight of factor 6 that they think of.

d: bystanders' thoughts about the weight of factor 7 that they think of.

e: bystanders' thoughts about the weight of factor 8 that they think of.

s: whether the factor 5 given by bystanders is true or not.

n: whether the factor 6 given by bystanders is true or not

u: whether the factor 7 given by bystanders is true or not

v: whether the factor 8 given by bystanders is true or not

We assume that s, n, u, v are either 0 or 1.

Then,

$b*s$ represents bystanders' propensity to act of providing help when considering the first factor.

Using the same way, $c*t$, $d*u$, $e*v$ represents the propensity to act of providing help when considering the second, third, and fourth factor respectively.

Then,

$b*s+c*t+d*u+e*v$ is the final propensity to provide help when combining four factors, which is the propensity to act(A).

The following are all the cases obtained through enumeration.

Table 1*Cases of Propensity To Act while The Assessment of Factor Does Not Change*

proportion of factor importance /the assessment of factor	factor 1(whether the person who needs help is similar to him)	factor 2(whether he stays in a remote area where fewer people prefer to enter)	factor 3(whether he is in a hurry)	factor 4(whether they know each other)	A(propensity to act)
Circumstance1 (C1)	0 /1	0.1 /0	0.2 /0	0.7 /0	0
C2	0 /0	0.1 /0	0.3 /0	0.6 /1	0.6
C3	0 /0	0.1 /0	0.4 /0	0.5 /1	0.5
C4	0 /0	0.2 /0	0.2 /0	0.6 /1	0.6
C5	0 /0	0.2/0	0.3 /0	0.5 /1	0.5
C6	0 /0	0.2 /0	0.4 /0	0.4 /1	0.4

Note. This is partially the table of propensity to act when considering these four factors. This table displays all of the circumstances of the proportion of factor importance while the assessment of factor remains the same.

Table 2*Cases of Propensity To Act while the Proportion of Factor Importance Does Not Change*

proportion of factor importance /the assessment of factor	factor 1(whether the person who needs help is similar to him)	factor 2(whether he stays in a remote area where fewer people prefer to enter)	factor 3(whether he is in a hurry)	factor 4(whether they know each other)	A(propensity to act)
Circumstance1 (C1)	0 /1	0.1 /0	0.2 /0	0.7 /0	0
	0 /0	0.1 /1	0.2 /0	0.7 /0	0.1
	0 /0	0.1 /0	0.2 /1	0.7 /0	0.2

	0 /0	0.1 /0	0.2 /0	0.7 /1	0.7
	0 /1	0.1 /1	0.2 /0	0.7 /0	0.1
	0 /1	0.1 /0	0.2 /1	0.7 /0	0.2
	0 /1	0.1 /0	0.2 /0	0.7 /1	0.7
	0 /0	0.1 /1	0.2 /1	0.7 /0	0.3
	0 /0	0.1 /1	0.2 /0	0.7 /1	0.8
	0 /0	0.1 /0	0.2 /1	0.7 /1	0.9
	0 /1	0.1 /1	0.2 /1	0.7 /0	0.3
	0 /1	0.1 /1	0.2 /0	0.7 /1	0.8
	0 /1	0.1 /0	0.2 /1	0.7 /1	0.9
	0 /0	0.1 /1	0.2 /1	0.7 /1	1
	0 /1	0.1 /1	0.2 /1	0.7 /1	1

Note. This table listed all kinds of circumstances for different assessment of factors and the same proportion of factor importance.

By using table 1 and table 2, people can find all the propensity to act(A) that are formed by different permutation and combination of proportion of factor importance and the assessment of factor using the calculation method of the above math model.

After that, bystanders observe others' behaviors and update their beliefs to form a final one. By observing, they make a prediction about whether others have the tendency to provide help(watching whether the pace slows down, whether there is an intention to stop, and whether the eyes keep looking at the patient or the people around) and then think about whether they want to change their beliefs. Links between bystanders and the weight they put on each other's opinion

are represented by a trust matrix, T , where T_{ij} is the weight that the bystander i puts on bystander j 's opinion. Therefore, the trust matrix has a one-to-one relationship with a weighted directed graph, where there is an edge between i and j if and only if $T_{ij} > 0$. The trust matrix is random. Its rows are composed of non-negative real numbers, and the sum of each row is 1.

$p(t)$ represents the beliefs of bystanders after they observe whether other bystanders have a tendency to want to help and reconsider their probabilities of providing help for t times.
($t=0, \dots, N$)

What is worth mentioning is that for T , there exists an indirect influence path between any two bystanders with no periodicity.

$$T = \begin{matrix} & \dots & T_{11} & \dots & T_{1n} & \dots & \dots & \dots & T_{n1} & \dots & T_{nn} \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \end{matrix}$$

In this part, T_{ij} represents the trust placed by i on j .

The whole trust matrix T represents the trust placed by each bystander on others.

Let's consider the bystander with first time belief $p_1(0)$'s circumstance. She has an initial belief about whether to help, represented by $p_1(0)$. Likewise, for other bystanders, they all have the initial beliefs, too. After this bystander form belief about whether to help by herself, she starts to observe the surroundings and takes into consideration the proportion of the influence of others on her.

Her new probability about whether to help is

$$T_{11} * p_1(0) + T_{12} * p_2(0) + \dots + T_{1n} * p_n(0).$$

Similarly, when they observe and form a new belief again, the new probability is

$$p_1(t+1) = T * p_1(t)$$

For other bystanders, their probability of providing help uses the same way to calculate,

$$p_n(t+1) = T * p_n(t)$$

After that, the final belief about whether to provide help consists of their previous propensity to act and the probability after observing others:

$$\text{Decision}(i) = A(i) * p_i(n);$$

As a result, if the decision > 0.5 , bystanders will provide help, otherwise they will not help.

What is worth mentioning is that after bystanders observe and reconsider again, all bystanders' $p(n)$ will finally become the same value. Here is the proof.

When the bystander observes others' behaviors and forms new ones, his new belief is the weighted average of others' beliefs (the weights are the numbers in the trust matrix T , and the sum of each row is 1). The following factors influence bystanders' updated beliefs:

1. on-verbal signals (staring fixated on the victim or having a tendency walking towards the victim)
2. behavioral delays (slowing down)

For instance, when a bystander updates his beliefs, he mixes others' beliefs together according to the degree of trust and then comes up with his own new belief.

Suppose there are currently two bystanders whose beliefs are respectively a and b

When they refer to each other's beliefs (updated according to trust weights T_{12}, T_{21})

The first bystander's new belief:

$$p_1(0)' = T_{11} * p_1(0) + T_{12} * p_2(0)$$

The new belief of the second bystander:

$$p_2(0)' = T_{21} * p_1(0) + T_{22} * p_2(0)$$

Calculate the belief difference between the two bystanders:

$$\begin{aligned} |p_1(0)' - p_2(0)'| &= |(T_{11} * p_1(0) + T_{12} * p_2(0)) - (T_{21} * p_1(0) + T_{22} * p_2(0))| \\ &= |(T_{11} - T_{21}) * p_1(0) + (T_{12} - T_{22}) * p_2(0)| \end{aligned}$$

Because the sum of each row for T is $1(T_{11} + T_{12} = 1, T_{21} + T_{22} = 1)$, so

$$T_{12} = 1 - T_{11}, T_{22} = 1 - T_{21}$$

After substitution:

$$\begin{aligned} |p_1(0)' - p_2(0)'| &= |(T_{11} - T_{21}) * p_1(0) + (1 - T_{11} - 1 + T_{21}) * p_2(0)| \\ &= |T_{11} - T_{21}| * |p_1(0) - p_2(0)| \\ &\leq |T_{11} - T_{21}| * |p_1(0) - p_2(0)| \end{aligned}$$

Due to $0 \leq T_{11}, T_{21} \leq 1$, so

$$|T_{11} - T_{21}| \leq 1$$

In this way, if the trust that the first bystander places in the second bystander, or the trust that the second places in the first, is zero, their updated beliefs will still remain the same.

Additionally, if both bystanders have an extremely strong propensity to act—here defined as either 0 or 1—their updated beliefs will not change. Otherwise, the difference between $p_1(0)'$ and $p_2(0)'$ is smaller than that between $p_1(0)$ and $p_2(0)$, because $|T_{11} - T_{21}|$ is less than 1 in this scenario. This indicates that after one update, the belief gap between the two bystanders narrowed or remained the same (this only happens if either $p_1(0)$ or $p_2(0)$ is 0 and the other is 1). Thus, if the two people do not have really strong beliefs, the belief gap will narrow.

In the case of multiple bystanders, the belief difference of any two bystanders will be multiplied by a number less than 1 each time it is updated.

Suppose the first belief difference is d_0 , the second is $d_1 \leq c * d_0$ ($c < 1$), and the third is $d_2 \leq c * d_1 \leq c^2 * d_0 \dots$

As the number of updates increases, c^t will approach 0 (because $c < 1$), so the belief difference d_t will also approach zero.

This means that everyone's beliefs will eventually become closer and closer until they are almost the same.

Understanding the above things, let's use an example to illustrate how their final updated beliefs will converge.

Let's assume there are three strangers. No. 1 believes that his influence on his decision is $1/3$, on No. 2 is $1/3$, and on No. 3 is $1/3$. No. 2 believes that No. 1 has 0 influence on his decision, No. 2 has $1/2$, and No. 3 has $1/2$. No. 3 believes that No. 1 has $1/2$ influence on his decision. No. 2 has 0, and No. 3 has $1/2$.

Thus, we can make a matrix based on the trust placed by one bystander to others:

$$T = \begin{bmatrix} 1/3 & 1/3 & 1/3 \\ 0 & 1/2 & 1/2 \\ 1/2 & 0 & 1/2 \end{bmatrix}$$

Then, it is penetrating to envision that each bystander's first hand beliefs are different, so we try to figure out all circumstances (let 1 represent really wanting help, 0.5 represent still hesitating, and 0 represent not wanting help).

Let's assume that the first bystander has a first time belief 1, and the second and third bystanders have an initial belief 0.5. This can be represented through table 3:

Table 3

Bystanders' Initial Beliefs

	No.1	No.2	No.3
p(0)	1	0.5	0.5

Note. This table displays bystanders' initial beliefs as I assume.

After gaining their initial beliefs, their beliefs will change by observing others. For the first bystander, he observes others' behavioral changes, such as on-verbal signals, behavioral delays I listed above, to estimate others' beliefs about whether to provide help.

First, he defines the decision weight for each person (including himself) in determining whether to provide help: his own weight, the second bystander's weight, and the third bystander's weight are all set to $1/3$. On this basis, he calculates three separate values:

He multiplies his own initial belief by the proportion of his own perspective in the overall decision (which is his $1/3$ weight), and multiplying the second, third bystanders' initial beliefs by the proportion of their perspectives separately. After calculating these three products, he sums them up to obtain $p(1)$, which represents his updated belief after the first observation. The same calculation logic applies to the second and third persons: each of them also computes their own $p(1)$ (their respective updated beliefs after the first observation) through the exact same steps.

Table 4 shows their beliefs after making observation for the first time:

Table 4

Bystanders' Updated Beliefs after Observing for the First Time

	No.1	No.2	No.3
p(1)	0.667	1/2	0.75

Note. This table displays bystanders' first time updated beliefs. The calculating method is $p_1(1)=T *p_1(0)$, which is what I address and explain in the above part on Page 10.

After observing for the first time, bystanders form their beliefs and think further to confirm their beliefs. Thus, they try to observe the second time using the same way to calculate, as shown in table 5.

Table 5

Bystanders' Updated Beliefs after Observing for the Second Time

	No.1	No.2	No.3
p(2)	0.639	0.625	0.708

Note. This table displays bystanders' second time updated beliefs. The calculating method is $p_1(2)=T *p_1(1)$, which is what I address and explain in the above part on Page 10.

After observing and thinking for many times, they will confirm their beliefs finally, which is represented through table 6.

Table 6

Bystanders' Final Updated Beliefs after Observing for Many Times

	No.1	No.2	No.3
p(final)	0.667	0.667	0.667

Note. This table displays bystanders' final updated beliefs. The calculating method is $p_1(t+1)=T *p_1(t)$, which is what I explain in the above part. In this part, t approaches infinite, indicating that the bystanders observe and make decisions for many times.

Understanding this, Tables 7 to 10 present the remaining circumstances obtained through enumeration. It is important to note, however, that their beliefs converge if and only if everyone's belief exerts an influence on others'—in other words, no one's belief goes entirely unnoticed by others.

Table 7

Bystanders' Final Updated Beliefs 1

	No.1	No.2	No.3
p(0)	1	0	0

p(1)	1/3	1/2	0
p(2)	5/18	5/12	1/6
p(final)	2/7	2/7	2/7

Note. In this scenario, it assumes the first bystander has a first-time belief of 1, and the second and third bystanders have an initial belief of 0. The final beliefs are calculated as what I do in Tables 3, 4, 5, and 6, which is clearly illustrated on Page 10.

Table 8

Bystanders' Final Updated Beliefs 3

	No.1	No.2	No.3
p(0)	1	0.5	0
p(1)	0.5	0.25	0.5
p(2)	0.417	0.375	0.5
p(final)	0.44	0.44	0.44

Note. In this scenario, it assumes the first bystander has a first-time belief of 1, the second bystander has a first-time belief of 0.5, and the third bystander has an initial belief of 0. The final beliefs are calculated as what I do in Tables 3, 4, 5, and 6, which is clearly illustrated on Page 10.

Table 9

Bystanders' Final Updated Beliefs 4

	No.1	No.2	No.3
p(0)	1	1	1
p(final)	1	1	1

Note. In this scenario, it assumes that all of the three bystanders have first-time beliefs of 1. The final beliefs are calculated as what I do in Tables 3, 4, 5, and 6, which is clearly illustrated on Page 10.

Table 10

Bystanders' Final Updated Beliefs 5

	No.1	No.2	No.3
p(0)	0	0	0
p(final)	0	0	0

Note. In this scenario, it assumes that all of the three bystanders have first-time beliefs of 0. The final beliefs are calculated as what I do in Tables 3, 4, 5, and 6, which is clearly illustrated on Page 10.

Since bystanders observe others, their beliefs will be affected by others' behaviors.

Specifically, after having a first-time belief, when they observe others, their beliefs more or less will be affected by others' ones. In this way, the probability of their choice to rescue will gradually lean towards what others consider the probability, while at the same time, others are also being influenced. After about three or four times, bystanders will conform to their thoughts.

After observing and making new beliefs several times, bystanders' beliefs will be updated: They may either all want to help or refuse to help. (pay attention that these updated beliefs determined partially people's final decisions)

The above examples illustrate the formation of bystanders' updated beliefs in the presence of three bystanders. When more bystanders are involved, the influencing factors of the bystander effect—as mentioned in the first point of the Literature Review, namely diffusion of responsibility, pluralistic ignorance, and fear of evaluation—exert stronger effects. This occurs because as the number of bystanders increases, the perceived responsibility of each individual decreases, while the social pressure against taking incorrect action intensifies, thereby reducing their initial inclination to provide help.

As the initial belief or willingness to help diminishes, the final updated beliefs of bystanders—formed after observing others' inaction—also decrease. Consequently, their final probabilities of helping are more likely to be low, except in cases where certain bystanders have an especially high propensity to act. This dynamic explains why the probability of providing help is inversely proportional to the number of bystanders.

Crucially, their previous propensity to act is crucial in deciding whether bystanders prefer to provide help when they have the similar final beliefs. If their propensity to act is too low, whatever others do, they will not provide help. Likewise, if it's too high, they prefer to be the helper. Otherwise, when people are hesitating, observing others' behaviors and reconsiders again can finally change their decisions.

The following example displays that bystanders with similar final updated beliefs make distinct decisions.

Still for the previous example, they will combine this value to their previous propensity to act. For the circumstance in the second table and C1. If No.1's propensity to act is 0.1, his final decision is $0.9 \times 0.667 = 0.6003$, indicating he will provide help. For No.3, his propensity to act first may be 0.1, by multiplication, his final decision is 0.0667, indicating they will not help. But having a propensity to act between 0.7-0.3 will be affected by the surrounding environment and may finally change their decisions.

This explains why some bystanders firmly prefer to provide help and others do not. And for those who are hesitating, the surrounding may reinforce or undermine their thoughts.

Analysis

This model displays the process through which individuals observe someone in need, assess the decisions of others, and ultimately decide whether to provide help from a mathematical perspective. It highlights how situational factors strongly influence a person's propensity to act, playing a critical role in the final decision. At the same time, interpersonal factors—such as

observing others and re-evaluating one's initial beliefs—lead people to incorporate the perceived attitudes and behaviors of those around them.

Using the matrix mentioned earlier, we can see that individuals often end up aligning their beliefs with the group. However, the final decision is shaped by both situational and social influences. When one of these factors is particularly strong, the individual is less likely to change their initial inclination. On the other hand, when people are hesitant, the behavior of others can significantly influence their decision, either reinforcing or undermining their original intention.

This dynamic helps explain why, in situations where someone appears to need help, individuals often either join collective efforts or refrain from helping altogether, as they continuously observe and integrate the actions of others into their own decision-making. This process is clearly illustrated by the trust matrix and the subsequent calculations regarding bystanders' updated beliefs on Page 10 and in Tables 3 to 14. As shown in these tables, individuals with a strong inherent propensity to act tend to make quick decisions, a behavior demonstrated in the final example on Page 16. Moreover, Tables 3 to 14 clearly illustrate that when such a person steps in to help, hesitant bystanders are more likely to be encouraged to assist as well. Conversely, if the majority of bystanders show no intention to help, the group may collectively assume a passive role, with each individual waiting for others to take initiative.

Thus, the model clarifies how social conformity shapes helping behavior and contributes to extreme outcomes, such as cases where no help is offered despite clear need.

Discussion and Limitation

When examining real-world situations, there are additional factors influencing an individual's propensity to act that were not fully captured in this study. It is also worth noting that, for the sake of model simplicity, the assessment of each factor's influence was limited to binary values (0 or 1). Furthermore, when individuals decide whether to help, their initial belief may be affected by the behavior of others—but it can also be swayed by emotions or sudden personal factors, leading them to act independently without regard to others. This suggests that there may be other factors not currently addressed in bystander effect research that could play a significant role. Future studies should take such elements into account. The present approach also overlooks the nuance of hesitation—a state individuals may experience throughout the decision-making process. Subsequent research could incorporate hesitation time when calculating both initial and updated beliefs.

Nevertheless, overall, the model remains useful in explaining how situational factors influence individuals, the cognitive processes behind decision-making, and why people often conform to group behavior when witnessing someone in need of help.

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Stablecoins Under Stress: Political and Economic Uncertainty on Adoption Across Argentina and the United States By Angela Liu

Abstract

This paper examines how political and economic uncertainty shapes stablecoin adoption by comparing how adoption in Argentina and the United States correlates with economic and political uncertainty indices between 2018 and 2025. Using Google Trends data as a proxy for adoption and public attention, alongside uncertainty indices and USDC trading volume, this study analyzes how stablecoin adoption responds to shocks and long-term trends. This paper argues that stablecoin adoption in weaker economies like Argentina may come from structural responses to political and economic uncertainty, whereas in developed economies such as the United States, adoption is not strongly correlated with uncertainty and is rather driven by factors like financial innovation and efficiency. The findings show that in Argentina, adoption accelerates nonlinearly, consistent with adaptation to chronic inflation and currency instability, while uncertainty has limited short-term predictive power. In the United States, adoption is weakly linked to uncertainty and instead is more reflective of financial innovation and market trends. These results highlight the dual role of stablecoins: both as shields in unstable countries and as tools for efficiency in advanced economies. Overall, this paper highlights the force of stablecoins in the global finance market, as it has the power to strengthen strong economies or destabilize fragile ones. Policymakers must therefore recognize the multi-faceted nature of stablecoins and craft regulatory frameworks tailored to specific economic and political contexts.

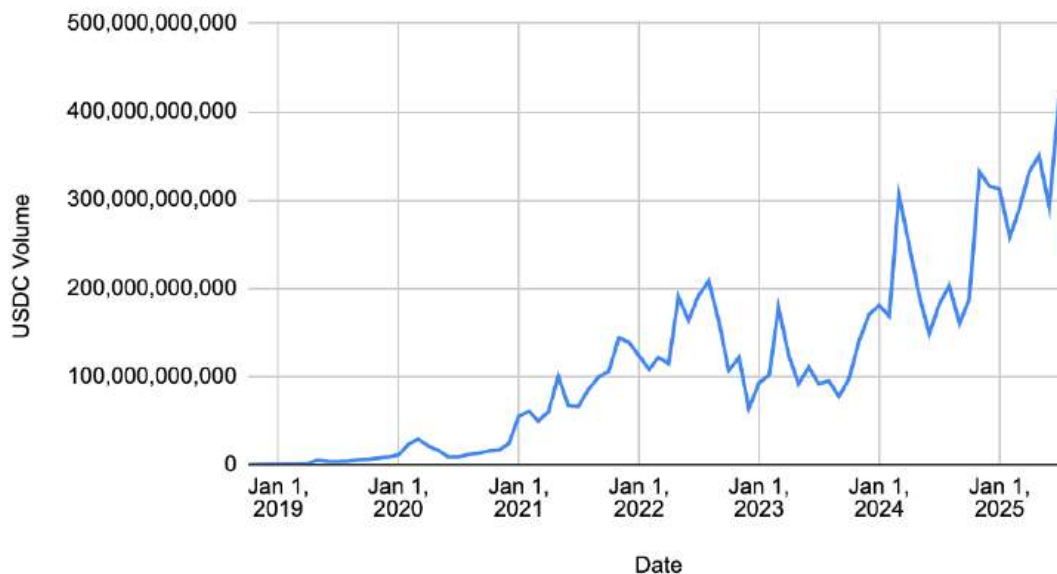
1. Introduction

In an era defined by the rapid digitalization of the global economy, stablecoins have emerged as a transformative force within the finance industry. In 2025, the total stablecoin market capitalization reached \$300 billion, which is a 75% increase from the previous year (McMullen and Oldenburg 1). Stablecoins are blockchain-based digital tokens designed to have a stable value by pegging themselves to assets such as the U.S. dollar. Unlike volatile cryptocurrencies such as Bitcoin or Ethereum, stablecoins are intended to serve as a more reliable medium of exchange, unit of account, and store of value. Their stability and global accessibility make them an alternative to traditional payment systems, especially in settings where financial infrastructure is underdeveloped or inaccessible. According to Alexander Lipton et al., stablecoins fall into three primary categories: fiat-backed, such as USDT and USDC, crypto-collateralized, such as DAI, and algorithmic variants like TerraUSD (2). These choices affect governance, transparency, and risk in investment. Arian Klages-Mundt et al. further emphasize that stablecoins expose different structural risks depending on their design, such as collateral mismanagement and de-pegging vulnerabilities, and thus call for a risk-based economic characterization of stablecoin types (2).

There are several major types of stablecoins that exemplify the diverse ways this technology is structured and governed. USDT (Tether) is the most widely used stablecoin with a market capitalization of \$102.016 billion and is pegged to the U.S. dollar with reserves held by a

private company (Otieno 7). USDC (USD Coin), operated by Circle and regulated transparently in the U.S., also maintains a 1:1 peg with the dollar. By contrast, DAI is a decentralized stablecoin managed by smart contracts on the Ethereum blockchain. Though these coins differ in terms of structure, they all share fundamental characteristics of being designed to offer price stability in an otherwise volatile crypto market.

Graph #1: USDC Volume from 2019–2025 (Yahoo Finance)



As shown in Graph #1, USDC volume has increased significantly in the past six years, highlighting the growing popularity and usage of stablecoins overall.

Traditionally, money serves three purposes: it is a medium of exchange, a unit of account, and a store of value (Smithin 3-5). Stablecoins fulfill all these three roles, but differ significantly from traditional fiat cash in that they are purely digital, can be transferred across borders without intermediaries, and exist on decentralized, blockchain networks. These differences make them more efficient in many ways, but also raise unique challenges relating to privacy, security, and monetary control.

This paper explores how stablecoins are being used in today's economy and examines their broader implications in the global economy. In an attempt to better understand the role of stablecoins in a rapidly changing global economy, a key question arises: how does uncertainty, both political and economic, influence stablecoin adoption? This paper compares a stable country (the United States) and an unstable country (Argentina) using political and economic uncertainty indices which consider factors like inflation to compare stablecoin adoption. This paper will argue that uncertainty plays a different role in shaping adoption across countries. In developing economies like Argentina, adoption is a response to long lasting periods of economic and political uncertainty, whereas uncertainty has little correlation with adoption in developed economies like the United States.

Understanding these dynamics is critical for policymakers formulating regulatory frameworks and institutions seeking to utilize digital financial innovations, particularly in regions where traditional financial infrastructure is lacking. This need is exemplified by the newly enacted U.S. GENIUS Act (The White House). Financial institutions and businesses are also evaluating stablecoins for faster payments, efficiency, and cheaper transactions (especially worldwide). Furthermore, consumers, especially in emerging and developing economies, may gain access to cheaper payment mechanisms and better stores of value. Stablecoins may also simplify the payment process for many.

2. Stablecoin Usage

2.1 Personal Transactions

Individuals, especially in high-inflation or regions with little existing financial infrastructure, are increasingly turning towards stablecoins for their day-to-day transactions. Due to their notion of stability, stablecoins are far more suitable compared to volatile cryptocurrencies for routine financial use. One of the most compelling advantages for personal users is their ability to enable near-instant, low-cost international transfers (Ante 2). Traditional remittance services often charge fees and can take several days to settle. Conversely, stablecoin transfers on blockchain networks typically go through in minutes and cost only cents or less per transaction. This makes them particularly useful for households in emerging and developing economies. Mohammad El Hajj and Imad Farran conducted a survey-based academic study across emerging economies (including Nigeria, Brazil, India, Indonesia, and Vietnam) using structural equation modeling (SEM) and found that cryptocurrency adoption significantly enhances financial inclusion and perceived economic empowerment (8). The study reveals positive, statistically significant relationships between cryptocurrency use and both empowerment and inclusive access to financial services. Individuals who lack access to traditional banking services, whether that be due to geographic isolation or branch scarcity, can transact digitally using only a smartphone and internet connection.

On the other hand, personal usage of stablecoins is not without risks. Regulatory frameworks in many jurisdictions remain underdeveloped, creating uncertainty around consumer protections. Many have noted that while stablecoins can simplify cross-border payments, their lack of central bank backing, reserve transparency, and official supervision poses monetary and operational risks. Additionally, financial literacy plays a role in stablecoin adoption for remittances. Ante reveals that demographic analysis indicates that stablecoin remittance users tend to be younger, more educated, and involved in higher-value transactions. However, if many in emerging or developing economies don't have these opportunities for financial literacy, they may be less intrigued to adopt stablecoins or participate in digital finance. Despite these numbers, retail usage remains a minority. J.P. Morgan estimates that only about 6% of stablecoin demand, approximately \$15 billion, stems from payments or retail activity, with the majority supporting trading, DeFi, or collateral usage (Singh).

3. Business-to-Business Transactions

Corporations are increasingly evaluating stablecoins for their efficiency in cross-border settlements. Unlike corresponding banking, with its steep fees and sluggish transfers, stablecoins offer near-instant settlement and reduced conversion costs. Firms such as Stripe, PayPal, and selected major banks have piloted integration of USDC or tokenized dollar transfers for business-to-business payments in trade and supply chains (Vatsa). Barry Eichengreen and Ganesh Viswanath-Natraj outline regulatory challenges in aligning stablecoins with central bank digital currencies (CBDCs), especially on cross-border remittances, as well as potential disruptions to monetary control in countries reliant on national currency sovereignty (2). Meanwhile, U.S. policymakers are actively forging a regulatory framework to clarify the status, reserve requirements, and institutional supervision of stablecoins.

4. Uncertainty and Its Impact on Stablecoin Adoption

At its core, political and economic uncertainty, such as contested elections, civil unrest, and hyperinflation, undermines trust in monetary systems, prompting individuals and businesses to seek more reliable alternatives of currency. In all those situations, stablecoins become a compelling alternative as they are digital, borderless, and unlike volatile cryptocurrencies, designed to maintain a stable value relative to fiat or commodities. For many countries, such as Argentina, Turkey, and Venezuela, stablecoins serve as a hedge against hyperinflation when formal access to stable foreign currencies is limited.

I posit three key factors that impact stablecoin adoption: currency substitution, risk-averse agents' diversification, and safe-haven behavior. In Argentina, during periods of peso depreciation, USDT usage spiked. When inflation increased, many Argentines converted their pesos into USDT, highlighting the idea of currency substitution (Garita 13). Currency substitution happens when there is a collapsing currency value, where individuals might shift toward stable digital tokens pegged to stronger currencies, which are more dependable, don't fluctuate as frequently, and are very stable. At the same time, these individuals engaged in risk diversification, which would reduce dependence on unstable assets like pesos by holding stablecoins which would offer more protection and liquidity (Díaz et al.). Finally, some literature has suggested that, despite the broader crypto market's volatility, stablecoins function more like safe-haven assets in crises (Zhang et al.). Thus, I hypothesize that higher political and economic uncertainty, such as in developing countries like Argentina, is positively associated with greater stablecoin adoption.

5. The Role of Development in Adoption

Stablecoin adoption is not uniform across the globe but instead reflects the broader economic and political environments in which individuals and firms operate.

In developing economies such as low-income or conflict-ridden countries like Nigeria, stablecoins offer financial access to populations without formal banking. Many of these regions have little access to formalized financial infrastructure, so mobile wallet penetration and crypto

transfers serve practical needs for remittances and savings storage. Stablecoins like USDT empower users to store value in U.S. dollars, conduct transactions, and send remittances.

In emerging economies experiencing high inflation, with Argentina being a prime example, citizens increasingly hold dollar-pegged tokens like USDT to preserve value and facilitate remittances. However, reliance on private digital currencies raises the possibility of currency substitution, which could hurt central bank authority. IMF analyses warn that unchecked stablecoin adoption in such settings may undermine monetary policy effectiveness unless adequately regulated (IMF).

By contrast, in advanced economies such as the U.S. and EU, stablecoins are mainly used for operational efficiency in trading, DeFi, and corporate settlements. Consumers and businesses already enjoy robust payment systems and strong financial infrastructure regardless of stablecoin adoption. Adoption, however, is driven by innovation goals rather than incentives of financial inclusion.

5.1 Comparing the U.S. and Argentina

The paper focuses on Argentina and the United States (emerging and advanced economies, respectively) because they represent polar extremes in terms of monetary stability, institutional credibility, and consumer incentives to adopt stablecoins.

Argentina has faced chronic macroeconomic instability for decades, with inflation often exceeding 100% annually and recurring crises of confidence in the peso (IMF). Argentina has a long history of political and economic volatility, chronic inflation, currency controls, and frequent recessions. Stablecoins are widely used here as a hedge against peso depreciation. Stablecoins pegged to the U.S. dollar have become a substitute for both cash savings and cross-border remittances.

The United States, by contrast, is the world's largest economy with relatively stable inflation and well-developed financial infrastructure. Here, stablecoins are used primarily for efficiency and innovation: traders use them to settle positions in decentralized finance, and firms like PayPal and Stripe have integrated USDC for payments. The U.S. also sets the regulatory tone for global markets, as shown by the 2025 GENIUS Act, which established reserve and audit standards for stablecoin issuers. Studying the U.S. case highlights how adoption evolves in a setting with comparably less political and economic instability.

6. Model

The primary dependent variable of interest is how many people searched for stablecoins in Argentina (Ars_stablecoin) and the United States (US_stablecoin), proxied using Google Trends data. This is useful because Google search activity provides a real-time, high-frequency measure of public attention, which often spikes during episodes of economic or political instability. As prior work has shown, Google Trends data are often leading indicators of financial activity. Chio and Varian demonstrate that search interest can predict macroeconomic measures like unemployment claims, while Preis et al. show that changes in search behavior can forecast stock

market movements. Applying this logic, spikes in stablecoin-related searches likely reflect surges in attention and adoption during times of economic distress or financial innovation. The volume variable is the trading volume of USDC (sourced from Yahoo Finance). This represents “hard” financial data and captures demand for stablecoins in actual transactions rather than just search behavior.

To capture uncertainty, I include three main indices:

- 1) EPU_ARG_foreign, an economic policy uncertainty index focused on Argentina
- 2) BBD_MPU_Index, a measure of macroeconomic policy uncertainty in the United States using Access World News archives
- 3) Global uncertainty indicators. I also include trading volume, time, and time squared to control for broader market activity and long-term trends.

The BBD Monetary Policy Uncertainty (MPU) index for the U.S. and the Economic Policy Uncertainty (EPU) index for Argentina capture macroeconomic and policy-related uncertainty through newspaper coverage. The MPU index for the U.S. and the EPU index for Argentina both flag articles which contain terms relating to economics, policy, and uncertainty. Including these indices allows the model to test whether periods of macroeconomic uncertainty or increased political commotion impact stablecoin adoption.

Overall, this dataset combines both “soft” data (public attention, uncertainty indices) and “hard” financial data (volume). Its advantage is the ability to capture signals of instability, but its limitation is that Google Trends is normalized (not absolute search counts), and indices like the BBD_MPU and EPU_ARG_foreign may not perfectly reflect the economic and political conditions in Argentina and the United States.

The study period of 2018–2025 is chosen because it captures the formative stage of stablecoin markets as well as a range of economic and political shocks that make it possible to test the uncertainty hypothesis. In 2018–2019, major stablecoins such as USDT and USDC launched and began early scaling. Adoption was limited but growing. In 2020–2021, the COVID-19 pandemic accelerated digital payments globally, and crypto adoption surged as households sought alternative financial tools during lockdowns (Feyen et al. 5). In Argentina, the peso depreciated sharply, producing potential spikes in stablecoin or digital finance interest. Between 2022 and 2023, there was a wave of inflation crises in emerging markets, including Argentina, Turkey, and Nigeria. During this time, the TerraUSD also collapsed in May 2022, emphasizing both the promise and risk of stablecoins (Klages-Mundt et al.). In the period of 2024–2025, regulatory clarity improved in advanced economies, while adoption in emerging economies continued to accelerate, with active stablecoin wallet addresses surpassing 30 million worldwide (Coin Metrics). Overall, the 2018–2025 time period captures the transition from stablecoin introduction and experimentation to global integration, providing a sufficient number of observations to detect both long-term trends (via TIME and TIME²) and short-term responses to uncertainty shocks.

Five regression models were estimated:

1. Argentine uncertainty and Argentine adoption

Linear Model:

$$SEARCHES_c = \beta_0 + \beta_1(UNCERTAINTY_c) + \beta_2(TIME) + \beta_3(VOLUME) + \varepsilon$$

Quadratic Model:

$$SEARCHES_c = \beta_0 + \beta_1(UNCERTAINTY_c) + \beta_2(TIME) + \beta_3(TIME^2) + \beta_4(VOLUME) + \varepsilon$$

2. Model 2: U.S. uncertainty and U.S. adoption

Linear Model:

$$SEARCHES_c = \beta_0 + \beta_1(UNCERTAINTY_c) + \beta_2(TIME) + \beta_3(VOLUME) + \varepsilon$$

Quadratic Model:

$$SEARCHES_c = \beta_0 + \beta_1(UNCERTAINTY_c) + \beta_2(TIME) + \beta_3(TIME^2) + \beta_4(VOLUME) + \varepsilon$$

3. Model 3: Combined model – Argentina adoption as a function of domestic and U.S. uncertainty

$$SEARCHES_c = \beta_0 + \beta_1(UNCERTAINTY_{USA}) + \beta_2(UNCERTAINTY_{ARS}) + \beta_3(TIME) + \beta_4(TIME^2) + \varepsilon$$

7. Results

Table #1: Regression Results

	ARG (Quadratic)	ARG (Linear)	USA (Quadratic)	USA (Linear)	GLOBAL
UNCERTAINTY	-0.01953	-0.03.357	7.025e-03	1.605e-02	0.0211
	(0.01687)	(0.01818)	(1.415e-02)	(1.401e-02)	(0.0146)
TIME	0.9013	0.02956	-2.859e-01	2.381e-01	1.542
	(0.2217)	(0.07824)	(2.295e-01)	(5.710e-02)	(0.236)
TIME^2	-0.01017		6.456e-03		-0.0148
	(0.000245)		(2.744e-03)		(0.0028)
VOLUME	4.794e-14	6.320e-14	7.252e-14	5.077e-14	
	6.923e-14	(7.607e-14)	(7.481e-14)	(7.636e-14)	
INTERCEPT	-1.279	1.109e+01	3.333e+00	-5.564e+00	-10.589
	(4.119)	3.129e+00	(5.475e+00)	(4.073e+00)	(6.017)
R-squared	0.6079	0.519	0.2485	0.1945	0.464
DW statistic	1.077	0.90258	0.37991	0.37702	

Both a quadratic and a linear time trend were conducted. Since stablecoin adoption has not followed a simple linear trajectory, empirical records reflect distinct phases of acceleration and deceleration. A linear time trend would assume that adoption increases by a constant amount each period, which is sometimes inconsistent with the data. By including both a linear term (TIME) and a quadratic term (TIME²), the model allows for curvature and depth in measuring adoption. Many network effects and financial innovations initially accelerate adoption, as once exchanges, wallets, and remittance providers integrate stablecoins, new users can join with lower friction (Catalini & Gans 87-88). However, as adoption expands, growth rates tend to slow down because the pool of early adopters becomes saturated and regulatory constraints emerge (Arner et al. 4). In the regressions conducted in this study, the positive coefficient on TIME and the negative coefficient on TIME² capture exactly this trajectory: adoption rose rapidly at first but has begun to stabilize as stablecoins move from innovation into mainstream finance.

8. Discussion

The regression results provide important insights into the drivers of stablecoin adoption, particularly in Argentina, relative to the United States.

8.1 Time and Non-Linear Growth

The Argentina results are the most striking. In the quadratic regression, the coefficient on time is positive (0.9013, $p < 0.01$) while time² is negative (-0.01017, $p < 0.001$). This strongly supports the S-curve hypothesis of technological diffusion by Rogers (Rogers 23). In the early stages, growth accelerates rapidly as early adopters and innovators embrace the technology. However, as adoption diffuses through the population, marginal increases slow down. The negative time-squared coefficient captures this idea, suggesting that stablecoins may be transitioning from a more “niche” concept and tool into a mainstream financial instrument. This is consistent with global trends in stablecoin usage, as supply has increased immensely over the years. By contrast, the linear model produces a smaller positive coefficient on time (0.02956, $p < 0.05$) but fails to capture the curvature. The quadratic model also explains more of the variation in adoption as $R^2 = 0.608$ vs. 0.519, confirming that nonlinear trends better describe Argentina's behavior.

8.2 Correlation Between Uncertainty and Stablecoin Adoption

The performance of the uncertainty indices is mixed. For Argentina, the coefficients on EPU_ARG_foreign and BBD_MPU_Index are small and statistically insignificant. This finding initially appears counterintuitive, given Argentina's chronic inflation and frequent political volatility, which should increase incentives for stablecoin adoption. This suggests that stablecoin adoption in Argentina is not simply a reaction to short-term fluctuations in political or economic uncertainty. However, there are two plausible explanations.

First, the indices themselves may not capture the lived experience of Argentine households. As Bloom notes, uncertainty is multifaceted, and media-based measures like BBD_MPU reflect what many elites search for rather than everyday household behavior. In Argentina, currency controls and informal dollarization often drive ordinary citizens to seek stablecoins, but these pressures may not align perfectly with fluctuations in formal uncertainty indices.

Second, the negative coefficients may indicate a substitution effect. During moments of severe uncertainty, households may prefer hard cash over digital assets. Scholars show that in highly dollarized economies, physical dollar holdings still dominate crisis responses. Thus, stablecoin adoption may follow uncertainty with a lag rather than in real time.

By contrast, the United States regressions show low explanatory power (R^2 values between 0.19 and 0.25) and weak or inconsistent correlations between uncertainty indices and adoption. This suggests that in advanced economies, stablecoin usage is not primarily driven by local instability but by global market narratives, such as concerns over monetary policy, inflation, or regulatory crackdowns. This aligns with Yan Chen and Cristiano Bellavitis, who argue that U.S. stablecoin adoption is driven less by necessity and more by financial experimentation, investment opportunities, and fintech integration (1).

The combined model yields an intermediate result. While global uncertainty shows some association with stablecoin searches in both the U.S. and Argentina, the quadratic term is again critical. Early adoption accelerated rapidly, but the growth rate has since slowed, reflecting the normalization of stablecoins in the global financial ecosystem. Adoption is no longer confined to uncertainty and crisis settings, but has instead expanded into payment systems, business-to-business transactions, and DeFi markets.

These results are consistent with the fact that stablecoins are no longer used just in cases of uncertainty, but have become an integral part of global finance. The adoption of stablecoins has grown rapidly, with some stablecoins' market capitalization exceeding \$200 billion and global transaction volume now reaching trillions annually. Stablecoins deliver benefits: faster remittances, lower transaction costs, increased inclusion in underserved regions, and innovative payment solutions, especially for corporations. Recent data demonstrates remarkable growth in stablecoin engagement. Business-to-business stablecoin transactions have become increasingly more popular. Stablecoin usage in B2B contexts is now quantifiable and significant. According to the analytics firm Artemis, B2B stablecoin transactions had skyrocketed from under \$100 million per month in early 2023 to over \$2 billion per month by early 2025, implying an annualized run rate of \$36 billion. This marks B2B as the fastest-growing segment in stablecoin volume (Kuhn).

8.3 Implications for Measuring Uncertainty

The weak correlation between uncertainty indices and Argentina's stablecoin adoption may suggest that media-based indices miss out on key aspects of uncertainty experienced by households. Indices like EPU_ARG_foreign capture macro-level narratives covered by the media, whereas Argentina citizens themselves face pressures that are not always visible, such as limited access to dollars. These lived experiences may create incentives to adopt stablecoins that are not reflected in the traditional measures of uncertainty. Thus, studying financial behavior may require looking at alternative indicators, such as informal market activity or peso depreciation, rather than relying on indices,

9. Conclusion

The regression results demonstrate that in Argentina, stablecoin adoption has followed a quadratic trajectory, with rapid early acceleration that eventually stabilized. Crucially, uncertainty indices were not strongly correlated with adoption, suggesting that Argentines' use of stablecoins is not driven by short-term shocks but rather a structural response to persistent instability. In this environment, stablecoins likely function as an everyday financial tool for preserving the value of money and accessing the dollar in the face of inflation and recurring crises. Stablecoins are commonly used, not just during periods of uncertainty.

By contrast, in the United States, stablecoin adoption showed little relationship to political or economic uncertainty. Instead, usage patterns are better correlated with innovation, speculative markets, and finance trends. Stablecoins in advanced economies thus appear to function less as hedges against instability and more as technological and financial innovations with applications in payments and capital markets, as is evident by the adoption of stablecoins by payment companies such as VISA.

At the global level, stablecoins have become more normalized components of the financial ecosystems. Stablecoins are increasingly intertwined in personal and business-to-business transactions, especially among digital finance platforms. Together, these findings highlight that the role of uncertainty in stablecoin adoption is highly context-dependent. In fragile economies, adoption represents a long-run adaptation to systemic volatility, while in advanced economies, adoption reflects financial innovation and experimentation rather than macroeconomic pressures.

The policy implications are significant. For emerging markets, stablecoins may be vital in their financial system. They may, however, also pose risks of currency substitution if left unregulated, which is why it's crucial for policymakers to implement regulations to protect monetary sovereignty. For advanced economies, the challenge lies in designing frameworks that balance innovation with consumer protection and stability. Going forward, stablecoin integration into the global financial system demands robust regulatory clarity, transparency in reserve management, and consumer protections that align with banking standards. Studies show that successful adoption hinges on legal infrastructure and institutional trust. Without these factors, stablecoins could very well destabilize monetary policy or result in financial fragmentation, especially with the central bank.

Ultimately, stablecoins are not a monolithic phenomenon. Their significance and risks vary dramatically across contexts. As digital finance evolves and becomes even more prominent in every aspect of society, policymakers and institutions must recognize this heterogeneity to harness the benefits of stablecoins while mitigating their systemic and inevitable risks.

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From Fear to Freedom: A Scoping Review of Artificial Intelligence-Powered Virtual Reality Treatment for Phobias By Samantha Folk

Abstract

Phobias are common in the United States, interfering with daily living by dictating physical, mental, and emotional well-being. Successful treatment of phobias can lead to improved life quality, greater self-efficacy, and reduced anxiety. Virtual reality (VR) provides a safe, controlled environment for exposure treatment, while artificial intelligence (AI) enables real-time adaptation of the therapeutic experience. Together, these technologies enable real-time, adaptable scenarios for safe, effective, and individualized treatment. This review paper studies how the intersection of VR and AI can improve treatment for phobias. This study used IEEE Xplore and Medline databases, yielding a final sample of 14 papers from 2010 to 2014 after screening and applying eligibility criteria. Research shows acrophobia is the most common health condition, with AI inputs primarily consisting of physiological data and AI outputs focused on predicting affective states—such as fear levels in 5 out of 14 total papers, as well as electroencephalogram classifications, severity groups, cortical states, stress scores, social anxiety disorder, and arousal states in other papers—mostly through classification or prediction methods, while few studies directly modified the VR environment. The studied papers effectively use real-time data adaptations to personalize treatments, where future work could focus on more interactive AI agents and broader clinical studies; however, this review is limited by a small sample size, restricted database usage, and limited inclusion of varied terminology in the search string. Overall, combining AI and VR offers a promising new approach to phobia treatment, with the potential to improve access and outcomes of care.

Introduction

Phobias are the most common anxiety disorder in the United States, involving excessive fear of a specific object or situation (American Psychiatric Association). Phobias can limit daily activities and can affect behaviors at work, school, and in social situations by taking over physical, mental, and emotional responses (“Overview - Phobias”). This can cause avoidance and feelings of dread, worry, and distress. Phobias have an estimated prevalence of 6.2% in the United States, with the one-month prevalence ranging from 4.0% to 11.1% (J. H. Boyd et al.). Prevalence is the number of people in a population with a health condition or characteristic during a specific period of time (“What Is Prevalence?”). Younger individuals and people with low socioeconomic status (SES) have a higher prevalence rate (J. H. Boyd et al.). Less than 1 in 4 individuals suffering from phobia(s) receive treatment. This is due to various reasons, including the perception that phobias are manageable without medical intervention, concerns about stigma, and a lack of awareness regarding treatment options (de Vries et al. 1-2). Additionally, some individuals may be unaware of treatment options, or may avoid treatment because their phobias often occur in situations that can be avoided. Phobias are commonly caused by past incidents or experiences, long-term stress, exposure to phobic reactions during

early childhood, or genetic factors (Wang 1-2). Facing phobias can encourage growth towards developing a positive growth mindset, better self-esteem, and a stronger sense of self-worth.

Traditional phobia treatments include talk-therapy, prescription medication, and self-help interventions in which individuals can use strategies independently to manage or overcome their fears without professional help (“Treatment - Phobias”). Cognitive-behavioral therapy (CBT), an exposure therapy or desensitization, is widely used in phobia treatment due to its effectiveness (“Treatment - Phobias”). While “talk therapy” is sometimes used interchangeably with CBT, CBT is a specific type of therapy focusing on changing thought patterns and behaviors (“Treatment - Phobias”). In CBT, patients are gradually exposed to their phobia in a controlled and systematic way (“Treatment - Phobias”). The goal is to help them manage and reduce their fear through monitored, real-life exposure (“Treatment - Phobias”). Medications such as antidepressants, beta-blockers, and tranquilizers can also be prescribed to alleviate anxiety symptoms (“Treatment - Phobias”). As a self-help strategy, mindfulness techniques, such as meditation and deep breathing exercises, can help individuals manage anxiety symptoms (“Self-Help - Phobias”). Additionally, attending self-help groups provides support, which can help individuals cope with their phobias, through sharing and meeting with others (“Self-Help - Phobias”). Some may even do self-administered exposure techniques, such as going out of the house for a very short period of time to help with agoraphobia (“Self-Help - Phobias”). However, the practice of exposure therapy in traditional phobia treatments can be limited by structural barriers such as time, insurance, or logistics, or the therapist’s inability to contain their negative attitude towards the exposure therapy or their limited knowledge of the practice (Krzystanek et al. 2). Virtual reality can provide the potential to overcome these limitations (Krzystanek et al. 2).

Virtual reality (VR) is a simulated environment that is three-dimensional, computer-generated, immersive, and multi-sensory that replicates real-world or imaginary experiences (Abbas et al. 7; Cipresso et al. 2). As VR headsets become increasingly widespread, VR has been adapted towards creating simulated experiences that can be used to supplement traditional mental health therapies. The virtual environment provides a safe space to conduct and practice these activities, as the realistic environment allows patients to experience their phobias in a controlled environment tailored to their needs, which can be stopped any time, before facing a real-life scenario (S. Kim and E. Kim 26).

The foundations of VR technology began in the 1950s and 1960s through early simulation and immersive systems. However, it wasn’t until around 1989 that the concept of VR became formalized and Jaron Lanier coined the term “virtual reality,” where VR began gaining recognition in research and psychiatric treatment (Maples-Keller et al. 2). In the 1990’s and early 2000’s, VR began to be used for prolonged exposure therapy, and its first study on the efficacy of VR-based exposure (VRE) on acrophobia suggested that it was an effective method (Maples-Keller et al. 2). From there, there were more studies on VRE for other psychiatric conditions and anxiety disorders (Maples-Keller et al. 2).

As VR is becoming a recognized tool for phobia treatments, incorporating artificial intelligence (AI) can introduce dynamic, data-driven approaches in VR phobia treatments. AI

can be defined as a “simulation of human intelligence by a system or a machine” with the goal of developing “a machine that can think like humans and mimic human behaviors, including perceiving, reasoning, learning, planning, predicting, and so on” (Xu et al. 1). AI algorithms are developed and are modeled after humans’ decision-making process, ‘learning’ to make accurate classifications or predictions from available data (Stryker and Kavlakoglu).

With the combination of AI and VR, the possibility emerges of personalized VR therapies that are adaptable in real-time. AI can analyze patient-generated health data to inform highly individualized therapy plans that evolve with the patient's progress. AI-powered systems can enable more natural and engaging interactions within the virtual environment, making therapy sessions more immersive and potentially effective. Additionally, AI has the potential to support therapists in making informed decisions by generating detailed progress reports and providing real-time insights.

This scoping review examines digital therapeutics that combine VR and AI to address phobias. Our central research question is how AI-integrated VR therapies can be used to treat phobias. While prior reviews have highlighted the effectiveness of VR in the treatment of phobias, there is not a prior scoping review that studies the role of AI in such therapies. Therefore, this review studies how the incorporation of AI, especially machine learning and deep learning, with VR can provide effective treatment options for phobias. Challenges and opportunities in this field are discussed.

Methodology

Inclusion/Exclusion Criteria

The inclusion criteria for this review are as follows: 1) published after the year 2010, 2) must involve the use of VR and AI in conjunction for phobia treatment, and 3) must be published in peer-reviewed journals or conference proceedings. This review excludes review papers, meta-analyses, and non-English publications.

Keyword and Database Search

We conducted a comprehensive search using the IEEE Xplore and Medline databases. We used the following search query for both databases:

(“machine learning” OR “artificial intelligence” OR “deep learning” OR “AI”) AND
 (“virtual reality” OR “VR” OR “augmented reality” OR “AR”) AND (*phob* OR anx*
 OR “fear” OR “panic”).

Initially, we used PubMed, but it provided no relevant papers. To expand the search, we added augmented reality (AR) to the search query. However, this did not generate additional results. We then included anx* OR “fear” OR “panic” for PubMed, but this also did not generate additional results. We left AR and anx* OR “fear” OR “panic” to be included in the IEEE

Xplore and Medline database searches. In the end, none of the papers from the results in either database involved AR.

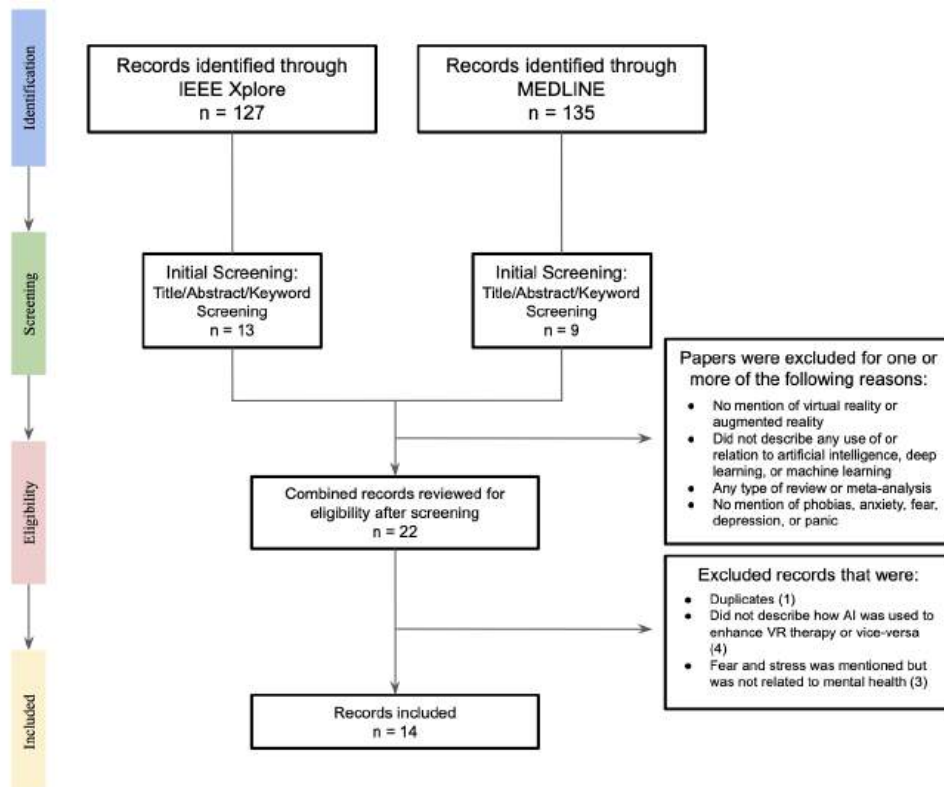
Filtering Procedure

We set the filter for the publication date on both databases to be from the year 2010 and after for a wider search range while retrieving relevant and recent papers. For the IEEE Xplore database, we included only conferences and journals. Although we did not set any filter for this, all results from the Medline database were only from conferences or journals. From this, there was an initial total of 262 retrieved papers, with 127 papers from IEEE Xplore and 135 papers from Medline.

Screening Process

We scanned the title and abstract, eliminating 240 papers due to little to no mention of phobias or similar conditions, little mention of VR or AR, the lack of description in the use of AI, deep learning, or machine learning, and any review papers or meta-analyses as per the exclusion criteria. Then we scanned the 22 remaining papers for eligibility. This process excluded 8 more papers for the following reasons: duplicates, the use of AI not being used to improve VR therapies or vice-versa, and papers mentioning fear or stress but were not related to mental health. This process resulted in a total of 14 papers that we reviewed (see Figure 1).

Figure 1. *Schematic of Study Criteria*



Results

Table 1 provides an overview of the various aspects examined in the reviewed papers.

Table 1. *Studies on the use of AI in VR phobia therapies and treatments*

Paper citation	AI input	AI output	Role of AI in VR therapy	AI performance (Accuracy, F1-score, AUC-ROC, Precision, Recall, MSE, etc.)	Health condition the VR is for
Cheng X, et al., “Classification and Analysis of Human Body Movement Characteristics Associated with Acrophobia Induced by Virtual Reality Scenes of Heights.” <i>Sensors</i> , vol. 23, no. 12, 2023.	Limb movements obtained from wireless miniaturized inertial navigation sensors (WMINS) network as a VR scenario runs	Acrophobia and non-acrophobia	Analyzes behavioral influences in terms of movements using VR exposure therapy in people confronted with VR scenes of extreme heights	94.64% accuracy	Acrophobia
Bălan O, et al., “An Investigation of Various Machine and Deep Learning Techniques Applied in Automatic Fear Level Detection and Acrophobia Virtual Therapy.” <i>Sensors</i> , vol. 20, no. 2, 2020.	Multimodal sensory data and a self-reported emotion assessment	Fear level	Automatic adaptation of exposure scenario according to the subject’s affective state	42.5%- 89.5% accuracy (training and testing)	Acrophobia
Ruso S, et al., “Analyzing EEG patterns in young adults exposed to different acrophobia levels: a VR study.” <i>Frontiers in human neuroscience</i> , vol. 18, pp. 1348154, 2024.	EEG data	Degrees of acrophobia	Evaluating levels of acrophobia in real-time	96%-99% (the range for convolutional neural network and artificial neural network models combined)	Acrophobia
Wang Q, et al., “Using convolutional neural networks to decode EEG-based functional brain networks with different severity of acrophobia.” <i>Journal of neural engineering</i> , vol. 18, no. 1, 2021.	EEG data collected by virtual reality (VR) exposure experiments	No fear of heights, slight fear of heights, and severe fear of heights	Evaluating the effectiveness of using EEGs to identify the degree of acrophobia using the VR treatment	Reached 98.46 ± 0.42%	Acrophobia

F. Hu, et al., “Research on the characteristics of acrophobia in virtual altitude environment,” 2018 IEEE International Conference on Intelligence and Safety for Robotics (ISR), Shenyang, China, 2018, pp. 238-243, doi: 10.1109/IISR.2018.8535774.	The volunteers’ EEG data	Fear level	Detects acrophobia level to ensure the safety of high-altitude workers using VR treatment	88.77% accuracy	Acrophobia
A. H. Gazi et al., “Respiratory Markers Significantly Enhance Anxiety Detection Using Multimodal Physiological Sensing,” 2021 IEEE EMBS International Conference on Biomedical and Health Informatics (BHI), Athens, Greece, 2021, pp. 1-4, doi: 10.1109/BHI50953.2021.9508589.	Electrocardiogram activity (ECG), Respiratory Rate, Electrodermal Activity (EDA)	Fear vs. no fear	Identify phobic anxiety in VR treatment	85% accuracy and F1-score	Anxiety
Mevlevioğlu D, et al., “Real-Time Classification of Anxiety in Virtual Reality Therapy Using Biosensors and a Convolutional Neural Network.” <i>Biosensors</i> , vol. 14, no. 3, 2024.	Physiological information	No anxiety vs. mild anxiety vs. severe anxiety	Differentiates three levels of anxiety during VR exposure therapy treatment	75% accuracy	Anxiety
Rahman MA, et al., “Enhancing biofeedback-driven self-guided virtual reality exposure therapy through arousal detection from multimodal data using machine learning.” <i>Brain informatics</i> , vol. 10, no. 1, pp.14, 2023.	Electroencephalogram (EEG) and heart rate variability	Arousal states	Triggers calming activities to allow individuals to cope with and overcome distress during VR exposure therapy	87.5% accuracy	Public-speaking anxiety (PSA)
A. Aljabri, D, et al., “Overcoming Speech Anxiety Using Virtual Reality with Voice and Heart Rate Analysis,” 2020 13th International Conference on Developments in eSystems	Voice and heart rate	Fear vs calm	Quantifies progress of the user over several training sessions during the VR treatment	89%-96% accuracy	Speech anxiety

Engineering (DeSE), Liverpool, United Kingdom, 2020, pp. 311-316, doi: 10.1109/DeSE51703.2020. 9450783.					
Chun JY, et al., “Prediction of Specific Anxiety Symptoms and Virtual Reality Sickness Using In Situ Autonomic Physiological Signals During Virtual Reality Treatment in Patients With Social Anxiety Disorder: Mixed Methods Study.” <i>JMIR serious games</i> , vol. 10, no. 3, 2022.	In situ autonomic physiological signals from VR treatment sessions	Severity of anxiety	Provides severity levels of specific anxiety symptoms and VR sickness during VR treatment	F1-score of 0.8421 for logistic regression model, 0.7619 using the naïve Bayes classifier, and 0.7059 using the random forest model	Social anxiety disorder
Liao G, et al., “Online classifier of AMICA model to evaluate state anxiety while standing in virtual reality.” <i>Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society</i> , vol. 2022, pp. 381-384.	Electroencephalo graphic (EEG) data	Cortical states	Detects changes in emotional states while standing during VR therapy	75% accuracy	Emotional states, like anxiety
C. Suresh, N. V, R. M, S. R. Regatte and S. Vesangi, “An Interactive Application for Detection and Treatment of Phobias Using Virtual Reality and Machine Learning,” <i>2022 International Conference on Recent Trends in Microelectronics, Automation, Computing and Communications Systems (ICMACC)</i> , Hyderabad, India, 2022, pp. 281-287, doi: 10.1109/ICMACC54824.2 022.10093580.	Tracking eye movements, mouth expressions, and monitoring heart rate	Fear level	Predicts fear level and mainly detects specific phobias during treatment of phobias using VR	76.2% accuracy	To help people diagnose their phobias and help them get treatment accordingly
A. D. Obukhov, et al., “Methods of Processing	Electroencephalo gram (EEG) data	Phobia reaction	Detects the presence of a	Accuracy up to 87%	Phobic disorders

and Analyzing EEG Data Based on Machine Learning to Determine Phobic Disorders,” 2023 <i>Systems and Technologies of the Digital HealthCare (STDH)</i> , Tashkent, Uzbekistan, 2023, pp. 84-89, doi: 10.1109/STDH59314.2023.10490943.	collected from the virtual reality		phobic reaction		
K. Tao, et al., “Automated Stress Recognition Using Supervised Learning Classifiers by Interactive Virtual Reality Scenes,” in <i>IEEE Transactions on Neural Systems and Rehabilitation Engineering</i> , vol. 30, pp. 2060-2066, 2022, doi: 10.1109/TNSRE.2022.3192571.	Physiological data (heart rate, electrodermal activity (EDA) and eye-blink rate) and self-reported stress ratings through a self-designed customized perceived stress questionnaire (SSAI) and wearable devices	No stress, low stress, high stress and continuous stress scores	Automate stress recognition of the patient during interactive VR scenes	Accuracy reaching 0.742	Stress disorder

Note. Rows in Table 1 are organized by phobia type, anxiety, or stress.

AI Inputs

Multimodal AI models that integrate various types of physiological data were prevalent in the reviewed studies. 6 out of 14 studies (42.86%) used 2 or more distinct modalities to make predictions related to affect.

All included studies (n=14) used one or more types of physiological data as input to the respective model. Table 2 shows the types of physiological data used as AI inputs.

Table 2. *Number of Papers Out of the Total Sample for Each Various Types of Data used as AI Inputs*

Type of data	Number of papers out of the 14 examined studies
Electroencephalogram (EEG)	7
Heart Rate	5
Tracking Movement	3

Electrodermal (EDA)	2
Electrocardiogram (ECG)	1
Respiratory Rate	1
Galvanic Skin Response (GSR)	1
Voice	1
Eye-blink Rate	1

Additionally, 2 out of the 14 examined studies included self-reported assessments or ratings; these were used as input for the respective AI model.

AI Outputs

All papers predicted some type of affect as the target prediction variable (output variable). 5 out of 14 studies (35.71%) predicted fear level as the output of the AI models. Other AI-enabled output variables included EEG classification (1) and severity categorization (4). This included stress levels (no stress, low stress, high stress) in 1 study, fear of heights (not fear of heights, slight fear of heights, severe fear of heights) in 2 studies, and Social Anxiety Disorder (SAD) in 1 study. In comparison, 1 study predicted different cortical states, 1 study predicted stress scores, 1 study predicted SAD, and 1 study predicted arousal states. 1 study included two AI outputs that classified stress levels and predicted stress scores (Tao et al., 2022). 7 out of 14 studies have an AI output related to fear. It was observed that the AI outputs were either classification or prediction of scores/regression; 7 out of 14 studies are prediction outputs, while 5 out of 14 studies are classification outputs. The majority of AI outputs focused on predicting fear levels or classifying various severity groups and affective states.

Building on the previous analysis, it was observed that 3 studies concentrated on identifying or detecting phobic reactions or stress responses. 1 study performed a dichotomous classification (Cheng et al., 2023), and another classified and predicted severity groups within the Internalized Shame Scale (ISS), Post-Event Rumination Scale (PERS), and Simulator Sickness Questionnaire (SSQ) subdomains (Chun et al., 2022). See Table 3 for a detailed and organized presentation of the AI outputs.

Table 3. *Number of Papers Out of the Total Sample for Each Various Types of AI Outputs*

Type of AI output	Specific type of AI output	Number of papers out of the 14 examined studies
Fear level	• Fear level	5

Classification/Categorization	• EEG classification • Stress levels (no stress, low stress, high stress) • Fear of heights (not fear of heights, slight fear of heights, severe fear of heights) • Social Anxiety Disorder (SAD) in one study	5
Prediction	• Different cortical states • Stress scores • SAD, • Arousal states	4
Other	• Identifying or detecting phobic reactions or stress responses • Dichotomous classification • Classified and predicted severity groups within the Internalized Shame Scale (ISS), Post-Event Rumination Scale (PERS), and Simulator Sickness Questionnaire (SSQ) subdomains	3

Enhancing VR therapy with AI

Only 2 out of 14 examined studies directly utilized AI to modify the VR therapy experience. The remaining 12 out of 14 (85.71%) studies, on the other hand, employed VR primarily to determine severity levels (4) or identify the degree of phobias (1), detect the type of phobia or cortical state (3), detect the phobia reaction and determine phobic disorders (1), analyze behavioral influences (1), quantify the user's progress (1) and automatic recognition of stress (1). Among those that used AI to modify the VR therapy directly, 1 study (Bălan et al., 2020) implemented automatic adaptations of the exposure scenario, and 1 study (Rahman et al., 2023) triggered calming activities during the exposure therapy.

Phobia Types

The most frequent health condition addressed in the reviewed papers was acrophobia (5 out of 14 studies). Other conditions included anxiety-related conditions (5 out of 14), general phobic disorders (2 out of 14), stress disorder (1 out of 14), and emotional states (1 out of 14).

Discussion

There are several notable trends in this field of AI-powered VR therapy for phobias over the past few years. A significant trend is the common use of multimodal AI models that integrate various types of physiological data, such as EEG, heart rate, and respiratory rate, with a few that predict affective states and tailor VR experiences in real-time. This allows for a more personalized and dynamic therapy session, enhancing the overall effectiveness of the treatment.

We noticed a particular focus on acrophobia, being the most commonly addressed condition in AI-powered VR therapeutics due to it being a common, widely prevalent phobia and becoming dangerous as there are more high-rise buildings, according to the examined studies addressing acrophobia. There is also an emphasis on using AI to classify and predict different severity levels of phobic reactions, which can aid in customizing treatment plans. Additionally, the field explores the potential of AI to provide real-time feedback and support to therapists, enabling more informed decision-making during therapy sessions. We had expected more research in the use of AI to modify the VR treatment directly. Instead, a large portion of the sample used AI to determine the outcome of the VR treatment.

Opportunity for Future Work

In our review, we did not observe the use of an AI agent for the patient to interact with, such as ordering food in cases of SAD. For those with SAD, ordering food is very difficult. VR, which can provide a safe and controlled environment, also enables repetition. The patient can practice overcoming SAD through ordering food as many times as needed without needing to order food or pay in real life. The AI agent could also provide encouragement during therapy. In addition, Maples-Keller et al. stated that the provider can “control the dose and specific aspects of the exposure environment to match the specific patient’s feared stimuli and optimize individualized pacing through exposures” (3). We also did not observe the inclusion of other phobias like aerophobia (fear of flying), agoraphobia (fear of being in places that may be difficult to escape from), and nyctophobia (fear of the dark). Aerophobia occurs in one in six adults, and among the public, 3-5% choose not to fly as a form of transportation (D. Boyd et al. 264). It was reported by Depla and co-workers that 38-44% of individuals with aerophobia find that it interferes with their daily life and social functioning (D. Boyd et al. 264). AI-powered VR therapy allows for the construction of the exposure that can be costly like an actual flight in the case of aerophobia (Maples-Keller et al. 3). For agoraphobia, the lifetime prevalence rate is 6.7% based on the National Comorbidity Survey (Magee et al. 159), and for nyctophobia, an estimate of around 40% of Americans are afraid to walk within a mile of their homes at night (Berke). For these phobias, VR, for the same reasons as stated for the inclusion of an AI agent especially in practice ordering food for SAD, provides a safe and controlled environment to conduct an exposure therapy as well as provides the ability to adjust the dose or specific aspect of the environment to the patient’s needs. Another opportunity for future work is that Rahman et al. used AI to trigger calming activities during the VR treatment. However, it was not clearly specified what type of calming activities were triggered, such as in treating arachnophobia, for example, the spider disappears or moves at a farther distance comfortable enough for the patient. However, most research did not adapt the therapy according to the AI output, presenting an opportunity for further work in the field of adaptive AI-powered therapeutics.

Limitations

A primary limitation of this review is that only a small sample size of papers was considered. As such, there may be trends in the field that were missed during this review. There were also a dearth of studies that operated in a clinical setting. We only used Medline and IEEE Xplore for identification of studies, although we note that we made an attempt to use PubMed but did not obtain any results. We did not use other databases such as Scopus, Web of Science, and ScienceDirect. The search query we used could have included terms like “fright” and “scare” that authors may have used that were related to phobias. Additionally, possible abbreviations were not included in the string, such as “ML” for machine learning and “DL” for deep learning. Nevertheless, the sample of papers that we studied highlighted emerging trends in this field.

Conclusion

This review sought to examine how AI-integrated VR therapies can be used to treat phobias by analyzing 14 relevant studies published from 2010 to 2024. The primary methods identified for using AI-integrated VR therapies to treat phobias include real-time adaptation of VR scenarios based on behavioral data and physiological data, such as EEG, heart rate, and respiratory rate. These adaptations are designed to enhance patient engagement and treatment efficacy by providing personalized therapy experiences. For instance, AI algorithms can adjust the intensity of the VR exposure based on the patient’s fear or anxiety levels, trigger calming activities during high-stress moments, and track the patient’s progress. Furthermore, AI models can classify and predict various severity levels of phobic reactions, which assists in making the therapeutic approach more precise. These findings emphasize and suggest the potential of AI to make VR therapy sessions more immersive, responsive, and effective, thereby offering promising advancements in phobia treatment. These studies also highlight the significant role of AI in enhancing the adaptability and personalization of VR-based therapies, paving the way for more sophisticated and patient-centric treatment modalities.

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Small Adolescent Population Lacks a Correlation Between Novelty-Seeking Traits and Social Media Use By Raegan Kubisch

ABSTRACT

Adolescents today spend unprecedented amounts of time on social media, raising concerns about addictive patterns and their underlying psychological drivers. Understanding why some adolescents are more vulnerable to large amounts of social media use is critical for developing healthier technology habits. Novelty-seeking is a personality trait linked to a desire for new and stimulating experiences, which social media platforms constantly provide. Adolescents aged 12–17 years completed two established surveys: the Early Adolescent Temperament Questionnaire-Revised (EATQ-R) to assess novelty-seeking traits, and the Bergen Social Media Addiction Scale (BSMAS) to measure patterns of social media use. Their answers revealed a lack of correlation between higher novelty-seeking scores and greater social media use. Future studies should take a multifactorial approach that examines how variables such as peer pressure, fear of missing out, self-esteem, and emotional regulation interact with personality traits like novelty-seeking in predicting problematic social media use. Overall, these results suggest that novelty-seeking is only one piece of a larger puzzle in understanding why adolescents develop problematic social media habits, which likely stem from a broader set of psychological and social factors.

INTRODUCTION

Social Media Addiction

Social media addiction refers to a pattern of compulsive and excessive use of online platforms that interferes with daily life, academic performance, and mental health. This issue is of particular concern during adolescence, a developmental period when technology habits are rapidly forming and vulnerabilities to addictive behaviors are heightened. Excessive use has been linked to sleep disruption, reduced academic focus, and increased symptoms of anxiety and depression (Kuss & Griffiths, 2020). Given these risks, social media addiction in adolescence represents a behavioral concern with significant implications for health and development. The *Bergen Social Media Addiction Scale* (BSMAS) defines it through six core symptoms of behavioral addiction: salience, mood modification, tolerance, withdrawal, conflict, and relapse. Salience can be described as when social media use becomes the most important activity in a person's life, dominating their thoughts, emotions, and behavior. Mood modification is when engagement with social media is used as a coping strategy, producing feelings of pleasure, excitement, relaxation, or relief from negative moods. Tolerance means that increasing amounts of time are required on social media to achieve the same psychological effect, reflecting a gradual escalation of use. Withdrawal can be classified as negative emotional states (irritability, restlessness, anxiety) that emerge when social media use is restricted or unavailable. Conflict is when excessive use leads to interpersonal problems, neglect of responsibilities, or other forms of

interference with daily life and functioning. Lastly, relapse is classified as failed attempts to reduce or control social media use, often followed by a return to previous patterns after temporary abstinence (Andreassen, Torsheim, Brunborg, & Pallesen, 2012; Andreassen, Pallesen, & Griffiths, 2017). Understanding social media addiction is therefore essential, as it illuminates how excessive online engagement can evolve from a common habit into a behavioral pattern with lasting developmental consequences for adolescents

Novelty-Seeking Traits

One potential personality-based risk factor for addictive social media use is novelty-seeking, the tendency to pursue new, exciting, and stimulating experiences (Kuss & Griffiths, 2020; Subedi et al., 2025). High novelty-seekers often display impulsivity and heightened sensitivity to reward, traits that have been associated with risky behaviors such as substance use and gambling (Montag & Walla, 2016). These behaviors are relevant to social media use because they share similar underlying reward mechanisms: each provides rapid reinforcement, immediate gratification, and unpredictable outcomes that fuel continued engagement (Montag & Walla, 2016; Andreassen et al., 2017). Just as substance use delivers chemical rewards and gambling offers intermittent wins, social media platforms provide likes, comments, and new content on variable schedules. For novelty-seekers, this combination of stimulation and reward unpredictability makes social media particularly compelling and potentially habit-forming. Social media platforms like TikTok, Instagram, and Snapchat are uniquely designed to appeal to novelty-seeking tendencies through endless streams of new content, notifications, and interactive features (Marques & Lima, 2023). As a result, novelty-seeking adolescents may be especially drawn to patterns of use that resemble behavioral addiction (Andreassen et al., 2017). Understanding the link between novelty-seeking and social media use is therefore central to this study, as it helps explain why certain adolescents may be more vulnerable to developing addictive patterns online.

Purpose of the Study

The present study investigates whether adolescents with higher novelty-seeking scores on the *Early Adolescent Temperament Questionnaire-Revised* (EATQ-R) also show higher social media addiction scores on the BSMAS. By measuring this correlation, this research aims to add to the current understanding of personality-based risk factors for digital addiction and inform healthier approaches to technology use. Based on prior evidence, we predict that adolescents who test higher in novelty-seeking will also score higher on measures of social media addiction.

LITERATURE REVIEW

Previous studies suggest that personality traits, especially novelty-seeking, shape adolescent behavior. The Early Adolescent Temperament Questionnaire–Revised (EATQ-R; Ellis & Rothbart, 2001) is a self-report instrument that evaluates key dimensions of temperament in adolescents, including effortful control, negative affect, surgency, and affiliativeness. The

surgency subscale specifically reflects novelty-seeking and reward-oriented behaviors, making it relevant for examining personality-based risk factors for social media addiction. Higher novelty-seeking scores have been associated with impulsivity, risk-taking, and seeking rewarding experiences (Marques & Lima, 2023; Subedi et al., 2025). For example, adolescents high in novelty-seeking may be more likely to experiment with new activities or take risks, underscoring the trait's role in reward-driven behavior (Montag & Walla, 2016; Andreassen et al., 2016). Social media use is a reward-driven behavior that has become a growing concern. The BSMAS is used to assess problematic patterns of use, including excessive time spent, preoccupation, tolerance, withdrawal, and interference with daily life (Andreassen et al., 2012; Andreassen et al., 2017). Prior research has identified several psychological and personality factors associated with higher scores on the BSMAS. For example, impulsivity and reward sensitivity have been linked to compulsive online behaviors (Marques & Lima, 2023), while low self-esteem and poor emotional regulation have been shown to predict problematic use (Kuss & Griffiths, 2020). Additionally, social factors such as fear of missing out (FoMO) and peer influence play a role in reinforcing addictive patterns (Andreassen et al., 2017). Because social media platforms provide a constant flow of novel and stimulating content, adolescents with high reward-seeking or novelty-seeking tendencies may be especially vulnerable to developing maladaptive use patterns (Marques & Lima, 2023; Subedi et al., 2025). Importantly, both novelty-seeking and problematic social media use have been independently associated with impulsivity and heightened reward sensitivity, suggesting that these shared mechanisms may underlie adolescents' susceptibility to addictive online behaviors.

Although research on both novelty-seeking and social media addiction has grown in recent years, few studies have directly tested their relationship using validated measures. Prior work on novelty-seeking has consistently linked the trait to impulsivity and risk-taking behaviors, including substance use and gambling (Montag & Walla, 2016). At the same time, research on social media addiction has identified psychological predictors such as low self-esteem, poor emotional regulation, and fear of missing out (Andreassen et al., 2017; Kuss & Griffiths, 2020). A small number of studies examining novelty-seeking in this context have reported modest positive associations, suggesting that adolescents who score higher on novelty-seeking may also be more vulnerable to compulsive social media use (Marques & Lima, 2023). However, the research base remains limited: while some studies have reported significant positive associations between novelty-seeking and social media addiction (Marques & Lima, 2023; Subedi et al., 2025), most large-scale studies have focused on other traits such as narcissism, self-esteem, or psychiatric symptoms (Andreassen et al., 2016; Andreassen et al., 2017). Moreover, there is limited work applying standardized tools such as the EATQ-R and BSMAS together, making it difficult to draw firm conclusions. The current understanding is that novelty-seeking is one potential personality-based risk factor for digital addiction, but it likely operates alongside broader social and psychological influences (Kuss & Griffiths, 2020). This study addresses this gap by testing whether higher novelty-seeking scores on the EATQ-R predict higher BSMAS scores among adolescents.

METHODOLOGY

Participants

The study included 34 adolescents aged 12–17, recruited through personal networks, school communities, and parent referrals. The participants had a mean age of approximately 15.85 years with a standard deviation of 1.48 years. The sample included 26 girls (76.5%) and 8 boys (23.5%). All participants provided consent, and parents or guardians gave informed consent prior to participation.

Instruments

Participants completed two established measures through an online Google Forms survey. Novelty-seeking was assessed using the Surgency subscale of the *Early Adolescent Temperament Questionnaire-Revised* (EATQ-R; Ellis & Rothbart, 2001), which includes items measuring excitement-seeking and a preference for new experiences. Social media addiction was measured with the *Bergen Social Media Addiction Scale* (BSMAS; Andreassen, Torsheim, Brunborg, & Pallesen, 2012), a six-item instrument capturing key components of behavioral addiction such as salience, preoccupation, withdrawal, tolerance, and interference with daily activities. Both measures were adapted slightly for clarity and age appropriateness. In addition, demographic questions (age, sex) were included to describe the sample and allow for potential subgroup analyses.

Data Collection and Analysis

Surveys were administered electronically, and informed consent forms were provided at the start. All responses were anonymous to protect confidentiality. Descriptive statistics (means, standard deviations, and ranges) were calculated for each measure. A Pearson correlation coefficient was used to test the relationship between novelty-seeking traits and social media addiction scores. Following Cohen's (1988) conventions, r values of approximately .10, .30, and .50 were interpreted as small, medium, and large effect sizes, respectively. In addition, a significance test of the correlation was conducted, producing a p -value to evaluate whether the observed association was likely due to chance. An alpha level of .05 was used as the threshold for statistical significance.

Ethical Considerations

The study was classified as low-risk. No identifying information was collected, and participants were informed of the study's purpose before beginning. Consent procedures followed ethical guidelines for adolescent research participation.

RESULTS

Descriptive statistics for the study sample ($N = 34$) indicated that scores on the EATQ-R Surgency subscale for novelty-seeking had a mean of 3.72 with a standard deviation of 0.53 and

ranged from 2.83 to 4.83. Scores on the Bergen Social Media Addiction Scale (BSMAS) had a mean of 3.12 with a standard deviation of 0.64 and ranged from 1.67 to 4.50. Participants reported spending an average of approximately 3.25 hours per day on social media ($SD \approx 1.2$), with reported use ranging from less than one hour to more than five hours per day.

A Pearson correlation analysis revealed a weak positive association between novelty-seeking and social media addiction ($r = 0.14$), which did not reach statistical significance ($p = 0.42$). Thus, the observed relationship falls within the “small” range, suggesting that novelty-seeking explains little of the variation in adolescents’ social media addiction scores. Scatterplot results (Figure 1) show a small upward trend, though the data points were widely spread. This variability likely contributed to the low correlation observed. Prior research has also reported modest associations between novelty-seeking and social media use, suggesting that while novelty-seeking may be a factor, it is one of several influences on adolescent social media behavior (Andreassen et al., 2017; Marques & Lima, 2023).

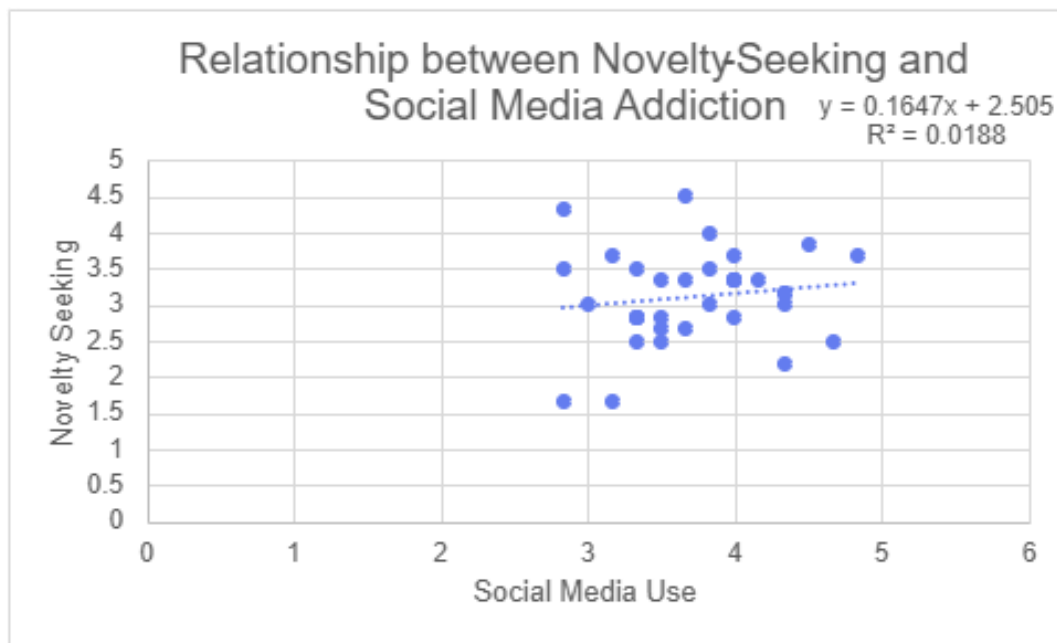


Figure 1. Scatterplot showing the relationship between novelty-seeking (EATQ-R scores) and social media addiction (BSMAS scores). A small upward trend is visible, but the wide spread of data points indicates only a weak positive association ($R^2 = 0.0188$).

DISCUSSION

The findings indicate a **weak, nonsignificant correlation** between novelty-seeking traits and social media addiction in adolescents. According to Cohen’s (1988) conventions, which classify correlations of approximately .10, .30, and .50 as small, medium, and large respectively, the observed relationship falls within the “small” range. Because the result was not statistically significant ($p > .05$), there is insufficient evidence to conclude that novelty-seeking and social media addiction are meaningfully related in this sample. This means that the weak positive

relationship observed could have occurred by chance rather than reflecting a true link between these traits. In other words, novelty-seeking may not be a strong or consistent predictor of social media addiction among adolescents, at least within the limits of the size and composition of this sample. While participants with higher EATQ-R Surgency scores tended to report slightly higher BSMAS scores, the relationship was not strong enough to draw firm conclusions. Still, the direction of the results is consistent with prior research suggesting that adolescents with high novelty-seeking tendencies are more likely to engage in behaviors that provide immediate reward or stimulation, including interactions with social media platforms (Andreassen et al., 2017; Marques & Lima, 2023; Montag & Walla, 2016). This alignment suggests that even weak or nonsignificant relationships may reflect a broader, underlying pattern worth exploring with larger or more diverse samples, emphasizing the complexity of digital behavior in adolescence. The weak, nonsignificant correlation observed in this study ($r = .14$, $p = .42$) is notably smaller than those reported in previous research. For instance, Marques and Lima (2023) found a significant positive correlation between novelty-seeking and social media addiction ($r = .28-.35$) using a temperament scale based on Cloninger's model, rather than the EATQ-R employed here, which may partly account for the difference in effect size. Similarly, Subedi et al. (2025) examined the relationship between broad personality traits (measured via a Ten-Item Personality Inventory) and Facebook addiction among adolescents in Nepal, though they did *not* assess novelty-seeking per se. In contrast, large-scale studies such as Andreassen et al. (2016, 2017) emphasize traits like narcissism and self-esteem, rather than temperament traits like novelty-seeking. Overall, while prior research often finds modest positive associations between personality and social media behavior, the present findings did not replicate those effects (perhaps due to methodological differences), small sample size, or limited variability in social media use.

This result contrasts with prior research that has reported modest but significant associations between novelty-seeking and problematic social media use (Marques & Lima, 2023; Subedi et al., 2025). One explanation may be the limited sample size of the present study, which reduced statistical power and increased the chance of a Type II error (saying there's *no effect* when really there is one, like a false negative). Another possibility is that novelty-seeking is on. Another important consideration involves the methodological limitations of the present study. Although the results point in the same direction as previous studies linking personality traits to digital behavior (Andreassen, Torsheim, Brunborg, & Pallesen, 2012; Andreassen et al., 2017), we must acknowledge several limitations, given that the correlation we found was weak and failed to meet statistical significance. The small sample size ($N = 34$) limited statistical power, making it difficult to detect stronger associations. In addition, the sample was recruited through personal networks and schools, resulting in a convenience sample that may not represent the broader adolescent population. The gender imbalance (76.5% female) further limited the generalizability of the findings. Prior research indicates that females tend to report higher social-media-addiction scores than males (Andreassen, Pallesen, & Griffiths, 2017), which could have biased the sample toward slightly higher overall addiction levels. However, because the

correlation between novelty-seeking and social-media addiction remained weak despite this, gender composition alone cannot account for the nonsignificant result. Reliance on self-report measures also introduced potential bias, as participants may have under- or over-reported their social-media use or novelty-seeking tendencies due to factors such as social desirability or inaccurate self-perception. Adolescents may minimize their screen time to appear more responsible or exaggerate novelty-seeking behaviors to align with perceived social norms. Additionally, recalling exact hours spent online can be difficult, which may have reduced the accuracy of reported data. In addition, most participants in this sample reported moderate social media use (an average of about 3.25 hours per day) which may have limited the range of BSMAS scores. With fewer participants reporting extremely high usage, potential correlations between high social media engagement and novelty-seeking may not have been fully captured. While the instruments used were well-established, minor adaptations for age appropriateness may have affected measurement validity.

Despite the methodological limitations of this study, the lack of a strong, positive correlation between novelty-seeking and social media addiction highlights other personality and psychological factors that may play a more prominent role in predicting problematic social media use. Prior research has identified traits such as impulsivity, low self-esteem, emotional dysregulation, and fear of missing out (FoMO) as stronger predictors of addictive online behavior (Andreassen et al., 2017; Kuss & Griffiths, 2020). These traits may influence how adolescents cope with stress, seek social validation, or respond to reward cues on digital platforms. Future research should therefore examine how these factors interact with personality traits like novelty-seeking to provide a more comprehensive understanding of vulnerability to social media addiction.

Future research should build on these findings by addressing methodological limitations and exploring broader psychological contexts. Larger, more diverse samples would improve statistical power and generalizability, while longitudinal designs could help determine whether novelty-seeking predicts social-media addiction over time or emerges as a consequence of excessive use. Combining novelty-seeking with other psychological and social variables—such as emotion regulation, peer influence, and reward sensitivity—may provide a more complete understanding of adolescents' vulnerability to problematic social-media engagement. Incorporating behavioral measures or neurocognitive tasks, rather than relying solely on self-report surveys, could further clarify how individual differences in temperament interact with digital environments.

Although this study found only a weak, nonsignificant relationship between novelty-seeking and social-media addiction, the findings still contribute to a growing body of research emphasizing that no single trait determines online behavior. Instead, they highlight the complexity of adolescent digital engagement and the need for nuanced, multidimensional approaches to prevention and education. Understanding the subtle interplay between personality and technology can ultimately guide healthier social-media use and inform interventions aimed at supporting adolescents' mental well-being in an increasingly digital world.

CONCLUSION

This study found a weak, non-significant positive relationship between novelty-seeking traits and social-media addiction in adolescents. While the link was not strong enough to establish a clear connection, the results point in the same direction as prior research suggesting that novelty-seeking may contribute to greater engagement with social media. Recognizing this potential relationship can help guide strategies for promoting healthier digital habits and highlights the value of considering personality traits when addressing adolescent technology use. Future research with larger and more diverse samples, including participants with a wider range of social-media use, should further explore how personality factors interact with environmental and social influences to predict problematic online behavior. Understanding these mechanisms is essential for developing early, personalized interventions that support adolescents' mental health and help prevent the escalation of online behaviors into addiction.

Figures

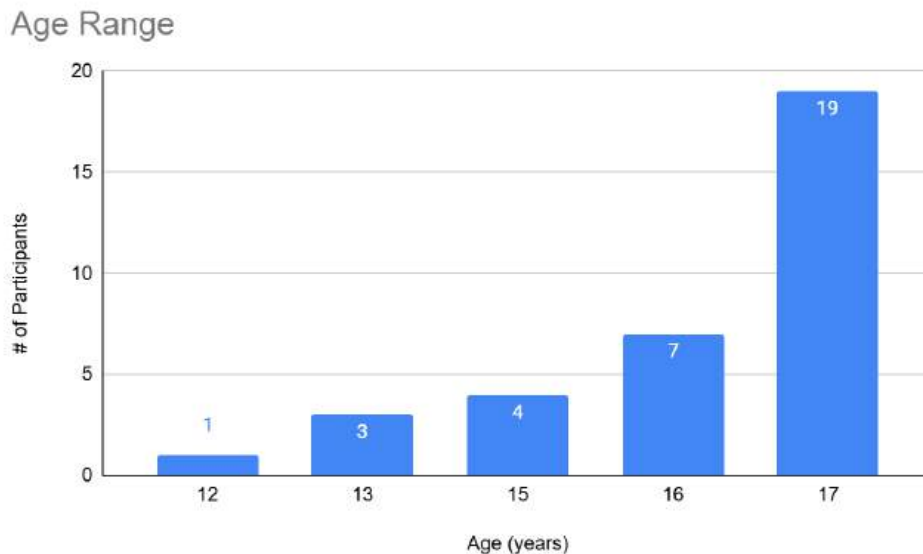


Figure 1
Age distribution of participants (ages 12–17)

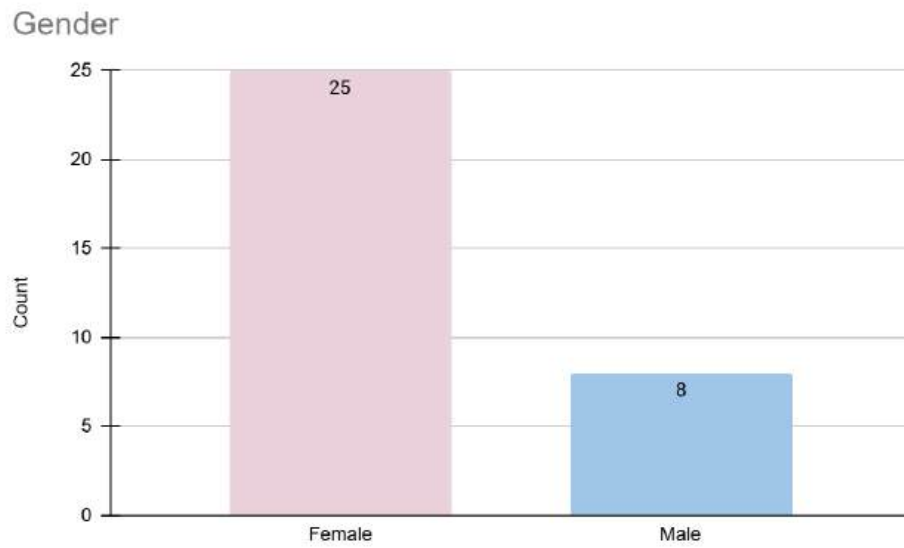


Figure 2
Gender distribution of participants.

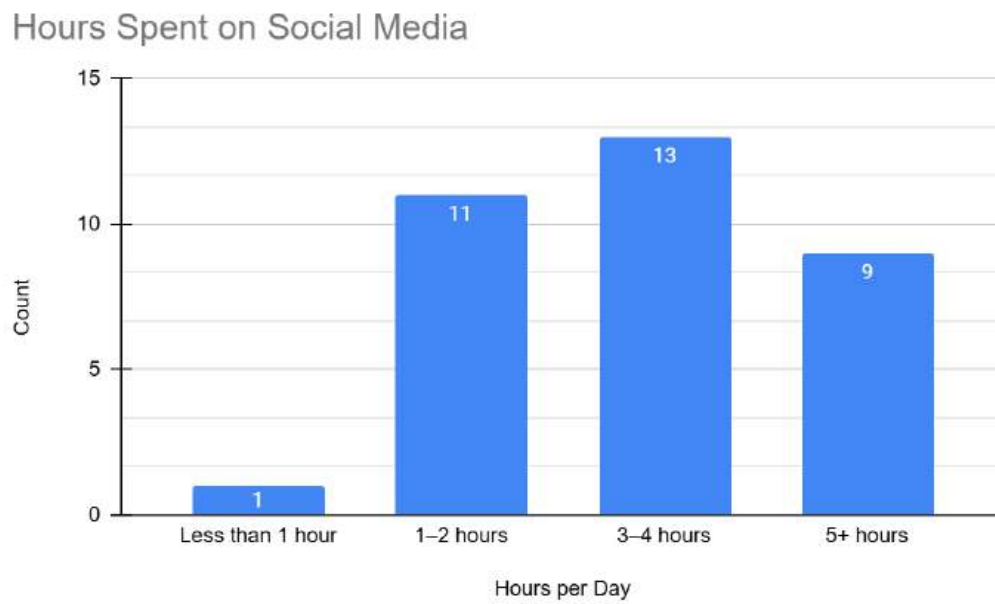


Figure 3
Distribution of participants' hours spent on social media per day.

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Common Stereotypes of Asian Women in Western Film By Ariana Marcarian

Abstract

This study analyzes how Asian women have been portrayed in Western film from 2005 to the present, focusing on whether harmful stereotypes remain prevalent. The researcher identified common stereotypes of Asian women—oppressed, model minority, submissive, invisible, and exotic—based on previous peer-reviewed studies that examined how these portrayals emerge through participant interviews. Drawing on these documented experiences, the study extended the inquiry to film, addressing the gap in research on Asian women's on-screen representation. A deductive thematic analysis was then applied to a randomly selected set of films to determine whether these stereotypes were prominently displayed. Results showed that three out of seven films actively challenged previously identified stereotypes, portraying Asian women as multidimensional characters with independent storylines rather than accessories to white leads. In contrast, four films continued to rely on reductive portrayals that reinforced these harmful stereotypes. The study concludes that although representation has improved in some instances, many works still reinforce unconscious bias, highlighting the need for more accurate and complex depictions of Asian women in film.

Introduction

There is a problem with the portrayal of Asian women in Western film. Despite some recent efforts to depict members of this group in a different light, even modern television continues to write stereotypical Asian female characters, including those of East Asian, South Asian, and Middle Eastern descent. According to a study done by the American Psychological Association, Asian American women felt discriminated against due to the way others viewed them through the lens of common generalizations. The study found that participants reported commonly being perceived and treated as exotic, submissive, and invisible (Mukkamala, et al.) Similarly, The Journal of International Women's Studies found that Asian women are also commonly viewed as oppressed (Tabaza). Finally, professor of psychology at Northwestern University, Edith Chen, finds that this group is also stereotyped as a model minority (Chen). But where exactly do these perceptions come from? Watching television is a universal pastime, however it also has the power to reinforce harmful and inaccurate stereotypes. It is important to address this idea of stereotyping of Asian women in television as The Electronic National Academy of Ukraine on Culture and Arts Management Staff Institutional Repository finds that television often escapes a person's conscious control and societal awareness, instead shaping the viewer's subconscious through universal stereotypes. In reality, all individuals are influenced by different forms of media (Halyna). This highlights how television shapes people's thinking, influencing what they believe based on what they watch.

A qualitative deductive thematic analysis of Western films with Asian female characters released from 2005 to the present will highlight how Asian women are stereotyped in television, and if these common stereotypes are prominent. Use of this modern time frame allows the

researcher to understand if the issue has undergone improvement, or if it is still overwhelmingly present. Additionally, some television productions created by South Korean filmmakers gained widespread popularity in the West, winning major American entertainment awards, and reaching millions of American viewers. As a result, these can be considered part of Western media influence despite their origins. The researcher included one of these productions in their final film set to ensure a sufficient amount of material for analysis, allowing for a more comprehensive conclusion.

All of these factors overall lead to the research question: How have Asian women been stereotyped in Western film from 2005 to the present?

Literature Review

In order to create a basic analysis of the topic prior to conducting new research, it is necessary to understand the state of the research done on the topic, and what area it has failed to investigate that led the researcher to choose their gap. Additionally, describing the efficiency of using the deductive thematic analysis method to accurately conduct research on the topic is beneficial.

The gap in the proposed research is a combination of gender and time. No studies have analyzed how Asian women specifically have been stereotyped in film, especially films released post-2005. Nicole Park from the Center for Scholars and Storytellers at UCLA found that “despite attempts at diversity in Hollywood movies and TV, Asian characters have often been portrayed as weak, nerdy, exotic, incompetent, powerless, and are seldom in the spotlight as leads” (Park). However, N. Park's study failed to focus on Asian women in a specific time period. To fill the gap, the established lens for this study is to focus on Asian women in films from the 2005 to the present rather than all Asian characters in any time frame.

Firstly, analyzing the existing research regarding common stereotypes of Asians in the media in general is essential before being able to analyze the specific ways Asian women are portrayed in film. Common stereotypes of Asians (not gender specific) were brought to light in Cal State Fullerton researcher Catherine Nailog's doctoral dissertation. Nailog included analyses of TV shows with East Asian main characters that suggested they were more likely “to speak with an accent, be family-oriented, obedient, studious, authoritative, attractive, and be positively portrayed and less likely to be manipulative, confrontational, sexually aggressive, and negatively portrayed” (Nailog). This highlights the numerous ways this group is regularly stereotyped. Moreover, delving deeper into harmful narratives discussing Asian women specifically can offer a better understanding of how stereotypes spreading through the media can in fact be harmful for an already underrepresented minority group. This is seen in an Oxford University case study analyzing the representation of Middle Eastern women in the general media. The study addresses how women's bodies are used as sexual commodities in Arab media as well as the fact that women have been “found to be the main negative image” used in the news, described as being immoral in some way or another. They are also commonly depicted as less-than or having little experience and intellectual capability (al-Ariqi). Presenting Middle Eastern women in this manner

in news sources or in widespread media that are perceived to be credible leads the public to subconsciously objectify them. However, professor of journalism at High Point University, Nahed Eltantawy, addresses this issue and discusses ways Asian women have fought against false narratives like these and improved their depiction in the media recently. The researcher discusses how the Arab Spring minimized the oppressed and exoticized image of Middle Eastern women and introduced the West to a new image of them, those who are “courageous, independent, and technologically savvy” (Eltantawy). Her research exemplifies the improvements seen in the issue in recent years, specifically in the Middle Eastern region.

Now that a general understanding of how Asians and Asian women are depicted in mainstream media has been established, it is important to shift focus to the portrayal of Asians in television specifically, as this is the central focus of the paper. Firstly, a Master’s of Arts degree thesis published by Aarhus University analyzes the portrayal of East Asian Americans in the television series *Fresh Off the Boat* (FOB), which aired from 2015-2020. Researcher, Priscilla Cheung, found these portrayals in FOB to “debunk some of the stereotypical characteristics of Asian Americans” (Cheung). However, some other stereotypes, such as the model minority ideal, were mocked in a satirical effort of highlighting how problematic they are, which still seemed to reinforce racist ideologies through their mere presence (Cheung). However, the series overall aimed to present an Asian family in a positive light for the audience to like and relate to. Further, another study by the University of Pennsylvania aimed to understand the impact of racial stereotypes in comedy. Results showed “viewers agreed that because it was, for example, an Asian character making a joke about Asians, it was acceptable” compared to if it were a White person making a joke about Asians. Viewers also noted that seeing Asians playing main character roles in a film was impressive “in an industry where Asians are practically invisible” (Park et al.). Therefore, Asians failed to criticize harmful stereotypes because they were grateful to be represented at all, highlighting systematic flaws. When comparing Cheung’s analysis of *Fresh Off the Boat* and J. Park’s findings, the necessary caution in addressing harmful stereotypes is exemplified, as there is a delicate distinction between spreading awareness about them and reinforcing them, which is often overlooked in modern television and media.

Moreover, the use of thematic deductive analysis would be most beneficial to finding and analyzing trends of stereotyping of Asian women seen in television. Thematic deductive analysis is defined by professor of psychology Saul McLeod as an approach in which “the researcher starts with pre-existing concepts or theories and uses them to guide the coding and theme development process” (McLeod). Therefore, identifying a set of themes before analyzing the media is more compelling than simply noting stereotypes during viewing, as it highlights how pervasive these portrayals are that preselected stereotypes, chosen without targeting specific examples, consistently appeared across all the television content examined. Furthermore, *The International Journal of Qualitative Methods* finds these types of visual mapping tools enhance the ability to identify and understand potential themes in relation to one another and the dataset as a whole (Naeem, et al.). By enabling researchers to visually organize and connect recurring patterns, these

tools not only help clarify individual themes but also reveal relationships between them and the broader dataset.

Methodology

To answer this research question and fill the presented gap most effectively, a qualitative deductive thematic analysis was conducted with a selection of seven movies, and utilizing a list from a Rotten Tomatoes article that highlighted the top 100 best Asian American movies (Rotten Tomatoes). The researcher then narrowed down to only movies that featured Asian women in lead or significant roles and fit in the time frame from 2005 to the present, resulting in 21 options. Next, the researcher inputted the list of 21 movies that fit the criteria into Google Sheets, randomized the range five times, and selected the top seven results (Appendix). Despite this high number of films on the Rotten Tomatoes list, the researcher chose seven movies total because of the limited timeframe for this project. The finalized list of movies was *Crazy Rich Asians*, *Aladdin* 2019, *Parasite*, *The Physician*, *Slumdog Millionaire*, *Amreeka*, and *Memoirs of a Geisha*.

In previous research in this discipline, researchers such as Michael B. Miles and A. Huberman from Arizona State University commonly utilize thematic analysis to collect and analyze data. However, when using a thematic analysis some biases need to be addressed. For example with using any kind of analysis with films, there can be outside experiences that can influence the implementation of words in a movie. Although it "outlines patterns or trends, and interpretive analysis" it can also lead to subjective perspectives (Miles, et al). This was avoided by using a deductive method, beginning with predefined themes grounded in existing theory or prior research, which helps minimize the influence of the researcher's subjective interpretations during data analysis. Before watching these films, the researcher created a chart regarding prevalent stereotypes as themes predefined by credible researchers: oppressed, model minority, submissive, invisible, exotic.

Findings

Stereotype	Definition
Oppressed	Described as being vulnerable, harassed, discriminated against, deprived, or suffering as oppressed victims of their societal systems (Tabaza, et al.).
Model Minority	The model mistakenly labels Asians as overly successful and overly represented in higher education or overachieving in certain roles. The model-minority stereotype groups all Asians together, and ignores the unique needs of subgroups and individuals (Chen).
Submissive	Depicted as passive, quiet, and compliant, often expected to stay agreeable and avoid asserting themselves. This relates to stereotypes of Asian women as obedient and easy to control (Mukkamala, et al.). This stereotype reduces Asian women to voiceless figures, reinforcing ideas that they lack independence or strength.

Invisible	“Experiences where Asian women are overlooked, lack representation, or are denied voice, agency, or power” (Mukkamala, et al.). This describes a form of marginalization where individuals or groups are excluded not just physically but socially and politically.
Exotic	Asian women are also stereotyped as a “geisha” or “lotus flower,” in which they are objectified as exotic women for men. The lotus flower stereotype is “based on western male sexual fantasy, a product of colonial and military powers interwoven with sexual domination” (Shrake).

Media Number	Movie Title	Release Date	Female Character
Movie #1	Crazy Rich Asians	August 15, 2018	Rachel Chu
Movie #2	Aladdin 2019	May 24, 2019	Princess Jasmine
Movie #3	Parasite	October 11, 2019	Choi Yeon-gyo
Movie #4	The Physician	December 5, 2014	Rebecca
Movie #5	Slumdog Millionaire	November 12, 2008	Latika
Movie #6	Amreeka	September 4, 2009	Muna Farah
Movie #7	Memoirs of a Geisha	December 9, 2005	Chiyo Sakamoto

Title of Media	Description of Key Events	Stereotype Identified
Crazy Rich Asians	Despite her success, Rachel is overlooked by Nick’s family for being not good enough, as she does not come from extreme wealth or a well known family	Invisible Stereotype
	Rachel is polite, modest, and avoids confrontation with Eleanor and other elders at first.	Submissive Stereotype
	Eleanor believes Rachel is selfish for choosing her own career and life path, suggesting traditional expectations for women to put family first and be self-sacrificing.	Submissive Stereotype
Aladdin 2019	Jasmine is expected to find a wealthy suitor to become sultan once her father dies. Despite her desire and capability to become sultan herself, she is prohibited from doing so because she is a woman.	Oppressed Stereotype
	Jasmine's beauty is emphasized, especially as Jafar forces her to marry him.	Exotic Stereotype
	Jasmine's early scenes show her being expected to stay silent and agreeable,	Submissive

	especially around her father and political figures. She is also expected to remain oblivious to major issues.	Stereotype
Parasite	Yeon-kyo doesn't stand up for herself in her household and relies on others, especially her husband, to make decisions. Overall she is a passive, obedient woman who fills the role of a wealthy "homemaker".	Submissive Stereotype
	Ki-jung (disguised as "Jessica") convinces her that the former housekeeper was mentally unstable and she must hire her as a replacement, which causes Yeon-kyo to immediately do so. She trusts Ki-jung's word without any skepticism or critical thought.	Submissive Stereotype
The Physician	Rebecca is betrothed to a man she does not want to marry despite being in love with Rob and addresses the arrangement as a "business deal".	Oppressed Stereotype
	Rebecca is ignored by men throughout the film and is only known as her fiancé's property.	Invisible Stereotype
	Rebecca is sentenced to death by stoning for having extramarital sex with Rob	Oppressed Stereotype
	Rebecca is quiet and rarely speaks up for herself	Submissive Stereotype, Invisible Stereotype
Slumdog Millionaire	Latika is kidnapped as a child, forced into a life of servitude, and subject to exploitation. Throughout the film, Latika is shown enduring violence, discrimination, and a lack of power to control her fate at the hands of Maman and Salim.	Oppressed Stereotype
	For much of the film, Latika remains silent, with her personal struggles overshadowed by the male characters' journeys. Her presence is defined primarily by her relationship with Jamal rather than her own story or character development.	Invisible Stereotype
Amreeka	Muna's life in Palestine before moving to America is portrayed as difficult due to her role as a single mother and her limited opportunities, her personal and professional life is restricted by societal and political circumstances	Oppressed Stereotype
	Muna's interactions with her brother and other male family members show a dynamic where she is expected to be compliant, particularly in family discussions about her son's future and her role in the family.	Submissive Stereotype
	When Muna begins dating a man in America, she often holds back her desires and opinions	Submissive Stereotype

	Muna's struggles with identity are often overlooked by the people around her. She is frequently marginalized, especially by her American colleagues and even some members of her family. Her voice and her personal journey are secondary to the American dream narrative and her son's future.	Invisible Stereotype
Memoirs of a Geisha	Chiyo's beauty and ability to seduce men are central to her identity and how she is valued in the film, especially in the context of Western fantasies of the "oriental woman."	Exotic
	Chiyo is sold to the okiya (geisha house) where she becomes part of a system that strips her of agency and independence.	Submissive Stereotype
	Chiyo is a "commodity" to be sold and used by men, and her personal desires and dreams are largely overlooked. Her agency is restricted by the roles and expectations placed on her.	Invisible Stereotype

Analysis

Recurring Theme 1: Oppressed Stereotype

In *Aladdin* 2019, the stereotype of oppression among Asian women is presented. Princess Jasmine struggles against patriarchal constraints keeping her from being able to rule Agrabah as Sultan. Therefore, she is expected to marry not based on love or passion, but rather as a political alliance with a man of great enough power to rule the country. Jasmine's oppression is further emphasized by the way others perceive her role as she is seen as a figurehead rather than as a capable leader. The way Jafar constantly undermines her ideas and beliefs and belittles her depicts how Jasmine clearly fits the oppressed stereotype. However, the implications of this stereotype shift throughout the movie. Jasmine does not accept her fate as a Sultan's wife, but instead fights for her rightful place as Sultan of Agrabah as well as for her right to marry someone she loves, regardless of political status. Jasmine's ambition to fight back against the traditions that seek to silence her work to overcome the stereotype of oppressed Asian women.

Moreover, this theme is also highly relevant in *The Physician*. Rebecca is depicted as a veiled, helpless side character who is engaged to a man she does not want to marry. Despite being in love with Rob, she is bound by the societal expectations of an arranged engagement and is expected to marry a man she does not love. Her forced adherence to this engagement reflects the oppressive norms of her society. When Rebecca engages in an extramarital affair with Rob, she faces severe punishment, being charged with adultery and sentenced to death. Although she eventually ends up with Rob following her fiancé's death, Rebecca does little to actively fight for her own desires or break free from the societal constraints imposed on her. The absence of significant storylines or personal agency for Rebecca suggests that she is not a fully developed character with her own voice or opinions. This reinforces the oppressed stereotype, demonstrating how women in this context are stripped of individuality and controlled by the men around them.

Next, in *Slumdog Millionaire*, Latika serves as another example of an stereotypically oppressed Asian woman in film. From a young age, she is kidnapped and forced into a life of servitude, facing constant exploitation and violence. She is constantly controlled by male characters throughout the film, leaving her fate largely out of her control. Moreover, Latika is portrayed as a victim, unable to break free from the oppressive structures that dictate her life. Even when she does find moments of personal freedom, like when she escapes from her captor, Maman, her choices and voice remain largely suppressed by the male-driven narrative as Salim continuously abandons and mistreats her. Latika's character serves as property for domineering men, and she is unable to do much to fight against their oppression herself.

Finally, In *Amreeka*, Muna is a clear embodiment of the oppressed stereotype. Her life is shaped by systemic barriers, societal expectations, and personal struggles that limit her freedom and independence. In Palestine, Muna's life is restricted by political instability, economic hardship, and social judgment as a divorced single mother. Seeking a better life, she immigrates to America, only to face a new set of challenges, including discrimination, underemployment, and xenophobia. Despite her education and work ethic, Muna is forced to take a job at a fast-food restaurant, highlighting how societal systems continue to oppress her regardless of her capabilities. Her personal choices are constantly scrutinized, whether by her brother, who expects her to conform to traditional family roles, or by American society, which marginalizes her identity and experiences. Though she shows resilience and quiet strength, the narrative often portrays her struggle for self-determination as an uphill battle against forces much larger than herself, making her unable to fully break away from them.

Recurring Theme 2: Model Minority Stereotype

In *Crazy Rich Asians*, Rachel exemplifies the model minority stereotype, particularly through her portrayal as the ideal "successful" Asian American woman. Rachel is depicted as highly educated (an economics professor at NYU) and hardworking, having achieved her success through merit and perseverance. However, despite embodying the "American Dream," Rachel's success is still not enough for Nick's family, who judge her based on her lack of wealth or prestigious lineage rather than her personal accomplishments.

Recurring Theme 3: Submissive Stereotype

Rachel also exhibits traits of a stereotypical submissive Asian woman. Rachel is initially portrayed as polite, modest, and conflict-avoidant, especially in her early interactions with Nick's family. Her respectful behavior toward elders like Nick's mother reflects traditional expectations for Asian women to be submissive and agreeable. Rather than directly confronting Eleanor's disapproval, Rachel initially tries to earn her approval through patience and humility, aligning with the submissive stereotype often expected of Asian women. Eleanor expects Rachel to fulfill the traditional role of a "homemaker," reinforcing the idea that women should be family-centered and obedient. However, Rachel's hardworking, independent lifestyle challenges this expectation. By valuing her own ambitions and identity, Rachel ultimately resists being defined by traditional

norms, breaking away from the submissive role imposed on her. Similar to her oppression, Jasmine in *Aladdin* 2019 is also forced into submission. Jasmine is discouraged from voicing her opinions or participating in political matters, particularly when she tries to interfere in Jafar's plans to attack Shirabad. She is dismissed and forced into silence as "better seen and not heard". However, Jasmine never gives into this idea of submissiveness and continues to be outspoken with her opinions and desire to rule and marry a man of her choice. Her character undergoes an even larger shift later in the movie, during the "Speechless" scene, where she rejects the expectation to stay silent. She stands up to Jafar and asserts her right to become Sultan, actively resisting the passive, submissive role that had been forced onto her.

Next, in *Parasite*, Yeon-kyo is an example of a submissive Asian woman. She is portrayed as such through her behavior within her household and her interactions with others. She relies heavily on her husband to make major decisions and rarely questions his authority or judgment. Further, she is portrayed as passive and naive, easily manipulated by those around her because of her failure to assert control or investigate situations herself. When Ki-jung, posing as an art therapist, falsely claims that the family's housekeeper is mentally unstable and she must be hired instead, Yeon-kyo immediately believes her without question, showing her naivety. Her role is confined to maintaining the home and appearing as a polite, well-mannered housewife, reinforcing the submissive stereotype that defines this idea. Yeon-kyo's character highlights how submissiveness and dependence can leave individuals vulnerable to manipulation, and therefore negatively portrays the stereotype.

Moreover, in *The Physician* Rebecca is also portrayed as submissive. She is expected to remain in the background and to not have strong personal opinions or desires. She is also expected to bear children for her arranged husband, though she does not wish to do so or even to be with him at all. Further, Rebecca is often silent in large groups and remains by her husband's side without fail. When she does break the norm and goes outside of her role however, with extramarital sex, she is sentenced to execution. This highlights the forced submission of Asian women, and the harsh consequences if they fail to comply.

Additionally, in *Amreeka*, Muna also exhibits submissiveness. Within her family, she is expected to agree with her brother's opinions, especially regarding her son's future and how she should behave in a new country. Rather than openly challenging her brother or other authority figures, Muna often chooses to stay polite and quiet, even when she disagrees. In her workplace, she faces discrimination and unfair treatment but rarely speaks out, instead enduring the mistreatment with patience in order to keep her job and provide for her son. Her dating experiences also reveal a tendency to suppress her own desires or discomforts, prioritizing harmony over confrontation. Muna's behavior reflects the submissive stereotype, where women are expected to maintain peace, avoid conflict, and sacrifice their own needs for the sake of family and survival, especially in a new and unfamiliar environment.

Finally, Chiyo in *Memoirs of a Geisha* also highlights the submissive stereotype. Sold to the geisha house as a child, she loses her freedom and becomes a commodity for men. Her life is controlled by the okiya, and she is expected to follow strict rules and training to become a

successful geisha. Instead of fighting for her own desires, Chiyo accepts her role and the harsh conditions, passively waiting for her chance to succeed. Even in her relationship with the Chairman, she doesn't assert herself but quietly hopes he will notice her. This passivity and her acceptance of her situation highlight the submissive stereotype, where women are expected to remain obedient and compliant, even when it means sacrificing their own happiness.

Recurring Theme 4: Exotic Stereotype

In *Aladdin* 2019, Princess Jasmine embodies the exotic stereotype in some ways. This is done through her portrayal as an object of male desire. Her beauty is a focal point of the film, and Jafar's attempt to marry her emphasizes this objectification. However, the live-action adaptation makes a better effort to avoid sexualizing the character, unlike the 1992 original cartoon version, which includes a heavy focus on Jasmine's physical appearance with the outfits she wears accentuating her curves and the animation emphasizing her seductive movements. This portrayal suggests that her value is largely defined by her physical appearance and the fantasy she represents, rather than her personal ambitions or intelligence. However, the changes made in the adaptation worked to break away from this stereotype and paint Jasmine in a new light.

Moreover, in *Memoirs of a Geisha*, Chiyo also embodies the exotic stereotype. From the start, her looks are emphasized, and she is valued more for her appearance than for her personality or dreams, with her beauty being the focal point of her identity. As she becomes a geisha, her worth is defined by how men see her, focusing on her physical attractiveness and grace. This portrayal aligns with the "lotus flower" stereotype, where Asian women are seen as delicate, mysterious, and meant to fulfill male fantasies. Chiyo's beauty is used to sell her as a commodity in the world of geisha, where she is expected to seduce and entertain men. This reduces her to an object of desire, taking away her agency and reinforcing the exotic image of Asian women as captivating but powerless.

Recurring Theme 5: Invisible Stereotype

In *Crazy Rich Asians*, Rachel experiences the invisible stereotype. She faces this through the way Nick's family, especially Eleanor, treats her. Despite Rachel's success as a professor and her accomplishments through hard work, she is often dismissed because she doesn't come from an old, wealthy family like they expect. Her achievements and intelligence are overlooked, and she is judged more for her background than for who she actually is. Throughout much of the film, Rachel tries to prove herself, but her efforts are mostly unseen or unappreciated by Nick's family. She is made to feel like an outsider who does not belong, no matter how capable or kind she is. This invisibility shows how Asian women, even when accomplished, can be ignored or undervalued if they don't fit into certain traditional molds.

Additionally, in *The Physician*, Rebecca is also treated as invisible. Throughout the movie, Rebecca's voice and desires are pushed aside by the men around her. Even though she is in love with Rob, she is forced into an arranged engagement with another man, and her feelings are barely considered in the decision. Her opinions are rarely asked for, and her life choices are

controlled by her fiancé. After Rebecca becomes pregnant out of wedlock, she faces harsh punishment, yet the men involved face no similar consequences, showing how little power or protection she has. Moreover, Rebecca's character exists to support Rob's journey rather than having her own goals or storylines. In this way, the film portrays Rebecca as invisible, treating her more as a background figure than an active part of her own life.

Next, in *Slumdog Millionaire*, Latika fits the invisible stereotype because she is often treated more like a prize than a person. Throughout the movie, her story is mostly told through Jamal's perspective, and her thoughts, feelings, and dreams are rarely shown. She is separated from Jamal and forced into a life where others control her decisions, but the movie focuses more on how Jamal feels about finding her rather than how Latika feels about her own life. Even when she is reunited with Jamal, it is more about completing his journey than showing her as an independent character. She does not have many scenes where she makes strong choices for herself, and her voice is missing from the main story. Instead, she is seen mainly as someone for Jamal to save, which makes her seem like a background character in his story.

Moreover, in *Amreeka*, Muna fits the invisible stereotype because her personal struggles are often overlooked by the people around her. Even though she faces many challenges, like finding a job, dealing with prejudice, and raising her son alone, most people in her life focus more on what she can do for them rather than who she really is. Her coworkers and even some of her own family members ignore her feelings and the sacrifices she is making. When she tries to start a new life in America, her hopes and worries are often pushed aside in favor of bigger ideas about the "American Dream" or her son's future. Muna rarely gets the chance to speak openly about her own dreams or to have her experiences taken seriously. Because of this, she often feels like she does not fully belong, and her voice is missing from the larger story. This makes her character an example of how Asian women are sometimes invisible to those around them.

Finally, in *Memoirs of a Geisha*, Chiyo fits the invisible stereotype because her true feelings, dreams, and struggles are mostly ignored by the people around her. From a young age, she is taken away from her family and sold into a life where her main value is based on how well she can serve and entertain others. The choices she makes are strictly controlled, and she rarely has the power to decide her own future. Throughout the story, Chiyo's personal voice is often silenced, and what she wants is seen as less important than what the men or powerful women around her expect from her. Even when she becomes a successful geisha, her success is tied to how well she fits into the role others have created for her, not her own dreams. The movie mainly shows her as someone who must quietly accept her situation instead of standing up for herself. This makes Chiyo invisible because she is treated more like a symbol than a real person with her own identity.

Connections to Foundational Literature

Overall, each of the analyzed films stereotyped Asian women in more than one way. Four out of seven of the analyzed films stereotyped Asian women as oppressed (Tabaza, et al.), one out of seven stereotyped them as a model minority (Chen), six out of seven stereotyped them as

submissive (Mukkamala, et al.), five out of seven stereotyped them as invisible (Mukkamala, et al.), and two out of seven stereotyped them as exotic (Shrake), with *Parasite*, *The Physician*, *Slumdog Millionaire*, and *Memoirs of a Geisha* making little to no effort to fight against the stereotypes presented against their female characters. In fact, they seemed to paint them this way almost unintentionally, as there is rarely acknowledgment of their victimization. This reinforces the validity of previous researchers' findings, confirming that these are recurring and widely recognized stereotypes. However, three out of seven of the films did, in fact, make efforts at fighting these stereotypes. For example, in *Amreeka*, while Muna faces various forms of stereotypical treatment from those around her, she is still characterized as a strong, independent woman who works for what she wants. Furthermore, *Aladdin* 2019 and *Crazy Rich Asians* engage in including stereotypes for the sole purpose of questioning or dismantling them and using them to empower female characters. Both Jasmine and Rachel prove themselves against the judgements posed against them and end up reaching their respective goals of Jasmine becoming Sultan and Rachel being with Nick while also maintaining her modern lifestyle. These noticeable improvements directly support Professor Eltantawy's study, which explores how Asian women have challenged false narratives and worked to reshape their media representation (Eltantawy), demonstrating that film has become one clear way this change is occurring. This is likely due to the fact that these two films are the only ones in the sample set – excluding *Memoirs of a Geisha* – that depict Asian women as main protagonists rather than as side characters. This highlights the idea that films characterize Asian women this way with intentions to fight against exploitation, however they do not have these same intentions when they are supporting characters. This connects to Cheung's study on *Fresh Off the Boat*, which found that the series generally portrayed the main ensemble cast in a positive light (Cheung); an expected approach, as viewers are naturally meant to relate to and support the central characters.

Addressing the Gap

As previously mentioned in N. Park's study, Hollywood has been "portraying the Asian American community in a more authentic light than before" (Park). However, this gap proved valuable, as it revealed that this positive portrayal does not apply equally to Asians of both genders, including in films released recently. This adjustment allows the researcher to have a deeper understanding and focus on the analysis of stereotypes to fit the objective of this study. Furthermore, with a specific gender and time frame in mind, it uncovers a new facet to the general topic of Asian stereotyping al-Ariqi, N. Park, and Cheung's studies that were investigated earlier. Based on the findings from the seven movies, there is a consistent pattern in how stereotypes related to different Asian ethnicities are addressed, aligning with the trends observed in similar previously mentioned studies; however, this study is able to analyze this topic with more recent productions and do so focusing on women specifically.

Conclusion

The findings of this study show that only three out of seven analyzed films actively worked to challenge or fight against stereotypes about Asian women, demonstrating that this issue remains highly relevant today. As discussed in the study from The Electronic National Academy of Ukraine on Culture And Arts Management Staff Institutional Repository, media can subconsciously influence viewers' beliefs and perceptions, meaning that these stereotypes continue to shape public attitudes even when not consciously recognized. The source highlights that “creating the whole picture of reality with all its contradictions can bring us to a comprehensive understanding of the world in all its diversity, which will help, in our opinion, overcome the crisis on a television screen” (Halyna). This overall indicates that media consumption has noticeable effects on people’s beliefs, therefore the stereotypes they see of Asian women may affect their real-world perceptions of this group.

Moreover, one major limitation of this study was the lack of Western media from the 2005 onward that featured Asian women as main characters. As a result, the analysis often had to rely on relevant side characters rather than central ones. This highlighted the larger problem of misrepresentation and underrepresentation of Asian women in Western media. Additionally, because there were not enough examples in Western television, the study also had to include Asian television output that were popularized in the West, as previously mentioned. Another limitation that emerged during the thematic analysis was the method itself, since the study was based on secondary data, the findings were ultimately subjective and shaped by the researcher’s interpretation.

Further, the research implies that while there have been improvements over time—for example, comparing the 1992 and 2019 versions of *Aladdin* shows more thoughtful representation—there is still significant progress to be made. A recommendation for future research would be to systematically compare older works with newer ones to measure exactly how much change has occurred, with the hypothesis that older media likely portrays stereotypes more harshly. Additionally, it would be useful to compare portrayals of Asian women with portrayals of white women in similar roles, to further explore how much of the stereotyping is racially motivated rather than simply based on gender. This study also points to the need for more representation of Asian women as main characters in Western television. Increased visibility could not only provide richer material for future research, but would also help dismantle long-standing stereotypes. Not only this, but ensuring that their portrayals when they are in background roles are equally as positive as their portrayals in main character roles would further improve the issue of subconscious influence among viewers.

Ultimately, the stories viewers see on screen shape the way they see each other, and themselves. By challenging old stereotypes and embracing authentic representation, television and film have the power to spark real change. The progress so far shows that change is possible, and with continued effort, future media can create a world where every story is given the voice and respect it deserves.

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Appendix

Movie Title	Release Date	Female Character
<i>Crazy Rich Asians</i>	August 15, 2018	Rachel Chu
<i>Aladdin 2019</i>	May 24, 2019	Princess Jasmine
<i>Parasite</i>	October 11, 2019	Choi Yeon-gyo
<i>The Physician</i>	December 5, 2014	Rebecca
<i>Slumdog Millionaire</i>	November 12, 2008	Latika
<i>Amreeka</i>	September 4, 2009	Muna Farah
<i>Memoirs of a Geisha</i>	December 9, 2005	Chiyo Sakamoto
<i>To All the Boys I've Loved Before</i>	August 17, 2018	Lara Jean Covey
<i>The Farewell</i>	July 12, 2019	Billi Wang
<i>Minari</i>	December 11, 2020	Monica Yi
<i>Always Be My Maybe</i>	May 29, 2019	Sasha Tran
<i>Wedding Season</i>	August 4, 2022	Asha
<i>White Rabbit</i>	January 19, 2018	Sophia
<i>Where Do We Go Now?</i>	September 11, 2012	Amale
<i>Meditation Park</i>	March 9, 2018	Ava
<i>Wish</i>	November 22, 2023	Asha
<i>Americanish</i>	April 22, 2021	Archana
<i>Journey From the Fall</i>	March 23, 2007	Phuong
<i>Happy Cleaners</i>	May 11, 2019	Hyunny
<i>The Handmaiden</i>	September 27, 2016	Sook-Hee
<i>Shirin in Love</i>	March 14, 2014	Shirin

Optimum Energy Generation Mix In Bulgaria By Nasko Shtonov

Abstract

Bulgaria's energy generation mix has been changing rapidly in the last decade. Solar photovoltaic power (PV) has grown from 3% share of electricity generation to 16% in 2025, while coal generation has fallen from 49% to 24%. This paper explores how Bulgaria can reduce its carbon dioxide (CO₂) emissions from coal generation while keeping electricity supply affordable and dependable. Using a simplified model based on actual Bulgarian data, I determine the maximum economically viable PV penetration to be 7.8 GW, supported by energy storage of 13.2 GWh. PV generation is 10.9 GWh of which 55% is fed to the grid, 43% used to charge battery energy storage systems (BESS) and 2% is curtailed. Consumers experience a benefit of €588 million per year or a 14% reduction in electric utility bills. Return on invested capital falls to the weighted average cost of capital for PV and is above the cost of capital for BESS. The share of CO₂ emissions from coal generation falls by 44% relative to 2019, which exceeds the EU guideline for the green energy transition in Bulgaria. Coal will continue to be used in the winter months but at lower levels than today, only in the four coldest months of the year, for a total generation of 6 GWh or 17% of demand. The analysis suggests there is no space for new gas capacity, while new nuclear power should be considered as replacement of existing reactors instead of capacity additions.

1. Introduction

Bulgaria has a population of about 6.5 million and uses around 35 terawatt-hours (TWh) of electricity per year. Most electricity is generated by the Kozlodui nuclear plant (about 41%) and lignite coal plants (about 24%). Solar power has reached 16% share in the last 12 months from July 2025 ("LTM"). The shares of other generation sources have been stable, with wind (3%), heating plants (CHP, 5%), and hydropower (6%) remaining small contributors.

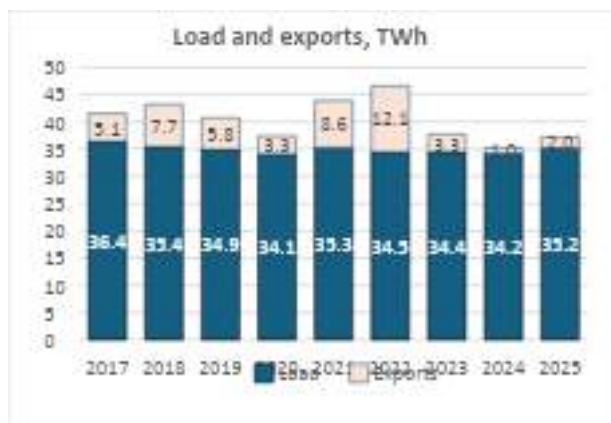


Figure 1: Bulgaria generation LTM July 2025

Source: *energy-charts.info*

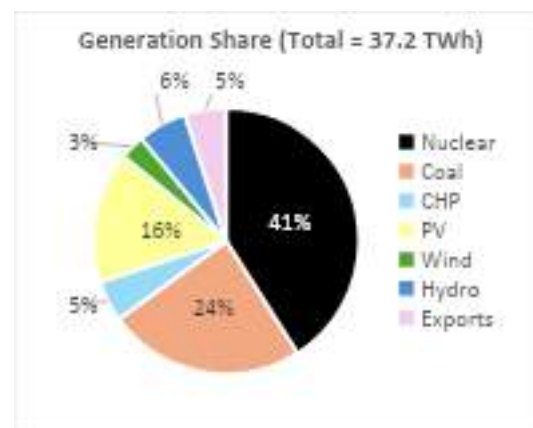


Figure 2: Generation mix

The country is well connected to its neighbors Romania, Türkiye, Greece, Macedonia, and Serbia. Temporal imbalances of daily/seasonal supply and demand have been met through exports/imports as Bulgaria has very few flexible power generation facilities. For example, there are no Combined-Cycle Gas Turbine plants (CCGTs) in the country. The generation mix in Greece and Romania is much more flexible (42% gas plant share in Greece and 21% in Romania). In a typical year, Bulgaria provides baseload power to the region with its nuclear and coal plants, while Romanian and Greek CCGTs provide flexible power generation when needed (i.e. absorb power exported from Bulgaria at noon, during the PV peak, then supply Bulgaria in the evening peak hours).

A major portion (75%) of the large power generation facilities are government owned or controlled, including the nuclear power plant Kozlodui (2 reactors at 1 GW power each, 15 TWh or 41% of the LTM energy produced), the Maritsa East 2 coal power plant (1.6 GW, 14% of the energy), the large hydro power stations (6% of the energy) and the only CHP (combined heat and power) plant (5% of energy), the 630 MW coal plant managed by AES through a long-term power purchase agreement (PPA) (9%). The remaining part of the energy is supplied by two independent coal plants, the 630 MW Bobov Dol plant and the 800 MW Maritsa East 3 plant and by many PV, wind, and small hydro independent power producers (IPPs). The average utilization of the coal plant capacity is below 30%. All producers are required to sell their output on the Bulgarian Energy Exchange at market prices; hence the wholesale market is fully competitive.

The EU requires Bulgaria to cut CO₂ emissions by 40% compared to 2019 levels by reducing lignite usage, which emits about 1.3 tons of CO₂ per megawatt-hour (MWh). Replacing coal too quickly could risk power shortages, especially during nuclear plant outages. The government is hesitant to force coal plant closures for security of energy supply reasons, as well as for social reasons (at least 20,000 people engage in mining coal, producing energy from coal, and maintaining coal plants). For example, the 2022 gas price shock increased power prices to the levels where all coal plants were profitable, and Bulgarian coal plants supported the entire region with energy. This can be seen in the exports section in Figure 1, when exports reached 12.1 TWh. A second, more recent shock occurred in November 2024, when due to delayed maintenance of one of the nuclear power plant reactors, the region again became short on energy, leading to an emergency government order to restart mothballed coal plants. Hence, any permanent reduction in coal output should be weighed against the country's security of supply needs.

1.1 Purpose of this study

The main goal of this study is to find an optimal mix of energy sources. In my context, we consider optimum to include a reduction in CO₂ emissions, keeping electricity prices stable or lower, as well as gain for investors. The only way to change the energy mix of a country is through investments in new generation sources. Therefore, the proposed changes to the mix should provide a positive return on investment, otherwise these investments are not likely to happen. The focus is on proven technologies that can be deployed in the country, such as power, battery storage, and potentially new nuclear or gas plants. The wind generation potential is also

evaluated. The approach assumes minimal government involvement since government policies in the last few years have been described as inconsistent. Due to the frequent government changes (six in the last three years), the country has not been able to follow a comprehensive energy strategy.

1.2 Literature review

Scholarly papers I reviewed do not provide direct answers to the questions investors ask: “How much capital should be deployed in which generation sources?” Some predict a generation mix, but the accuracy of their predictions is inconsistent 2-3 years after publication. Often this is either because they extrapolate past trends in aggregate without accounting for the hourly generation profile for PV or because they fail to model the actual costs to investors through adapting published levelized cost of energy (Lazard LCOE+, 2025) to local conditions. For example, Kacsor, E., et al. (2025) in *Integrating solar plants into the European power grid – What is the optimal capacity combination of PV and battery storage?* assume PV capex of €430/kW which is in line with market, and BESS capex of €570/kW for a 2h battery which is 2.5x higher than actual capex of BESS deployed today. They arrive at an optimal level of BESS penetration of 5% of installed intermittent renewables power. I believe the optimal level is significantly higher and the difference is driven by the assumed LCOE difference. Other papers put faith in new generation technologies that have not yet been commercialized yet, such as hydrogen or thermal energy, etc. My analysis focuses only on mature, investable technologies, such as PV and BESS.

The Bulgarian Electric System Operator (ESO) publishes an annual 10-year network development plan (ESO, 10-year plan, 2025) that discloses total connection capacity requested by investors. The latest ESO 10-year plan predicts 7.1 GW of new PV, 0.9 GW of new wind, and 4.8 GW (equivalent to 9.6 GWh of storage at 2h) of BESS grid connection requests for the period 2025-2030 but projects only a portion of these will be installed, specifically 35% of the PV requests and 80% of the wind requests. The transmission systems operator (TSO) also suggests an alternative scenario, with full elimination of coal by 2030, by meeting the winter peak demand with 1.1 GW of newly built CCGTs and 1.4 GW of imported power. However, the economics and investor return behind this scenario are not addressed in the government report. In this research, we suggest that new CCGT capacity is likely to be ineffective in the Bulgarian environment due to low projected utilization which makes positive return on investment unlikely.

Trifonova, M. et al., (2025) in *Flexibility Assessment of the Bulgarian Power Grid* highlights the importance of system stability and flexibility services as renewables increase dramatically, especially in the summer noon peak for PV. There are different technologies to provide these services, including converting some coal plant units into synchronous compensators that can provide system stability when needed. As those solutions are novel and not fully deployed yet, this model assumes a minimum amount of coal that needs to run throughout the year, for grid reliability reasons. Moving to high renewables penetration requires the provision of frequency control. The book notes that the Bulgarian system needs around 500

MW of power for primary and secondary frequency control that is currently provided by the coal plants. Since my model forecasts high BESS penetration, that will significantly exceed the reserve power requirement, I do not include reserve capacity as a constraint following the rapid growth in BESS capacity.

The *Bulgarian National Energy and Climate Plan* (NECP, 2025) is a key policy document that highlights 1) Bulgaria as one of the more energy intensive EU economies, suggesting significant improvements to energy efficiency are possible; 2) the importance of local energy security as provided by lignite coal capacity; 3) sets a target for renewable penetration of 35% by 2030 which is **equivalent to 25% for PV** after subtracting hydro (6%) and wind (4%).

The current model uses information from interviews with current and past industry executives based on actual data on capital and operating expenditure for current projects, which formed the basis of my LCOE cost calculations.

Consulting companies such as Baringa, Aurora and others forecast capture prices by technology to aid investors in their return-on-investment (ROI) calculations. They use sophisticated, iterative models run on a regional basis. I did not have access to such models for this research. Other papers highlight the importance of government action, including renewable support schemes, and grid connection development to accelerate the speed of energy transition away from fossil fuels. Governments often do not follow a straightforward plan, and investors would not wait for the perfect opportunity indefinitely. Thus, this paper aims to offer an optimum generation mix that is both economically viable and that depends as little as possible on government intervention.

1.3 Objectives of this study

Determining the optimal generation mix of a country is a complicated exercise that involves many considerations. My objective is to create a simplified but robust model that can help answer these questions. Since the mix can only be changed through investment decisions, I consider two main inputs to the model, PV capacity, and BESS capacity. For a given set of these inputs, the model computes utilization factors, new capture prices, investor returns and society benefits. Then I use the Excel Solver tool to vary the inputs until the target returns/benefits to society are achieved. The model adds complexity where it is needed and takes short cuts where the complications will not significantly impact the end results. A key objective is to make the model transparent and interactive.

2. Comparison of generation costs across technologies

The cost comparison is based on interviews with industry executives in Bulgaria and supplier data. Some assumptions are different from published industry benchmarks that do not take local conditions into account. I use LCOE as the comparison methodology adjusted for economic lifetime, utilization factor, and actual observed construction costs. LCOE is the Levelized Cost of Energy and aims to calculate the present-day cost per MWh of energy of building and operating a power plant over its projected lifetime. I use the simplified formula:

$$LCOE = \frac{CRF * CapEx + FixedCost}{Annual\ Energy\ Production} + VarCost$$

Where:

- LCOE is the cost in €/MWh
- Capacity factor is the amount of time a plant operates at maximum capacity
- CapEx is the initial capital expenditure in € '000
- FixedCost is the cost for maintaining and operating the plant per year in €/MW (power)
- VarCost is the cost in €/MWh for fuel, consumables, and balancing cost for intermittent sources. For energy storage, the variable cost includes the price of battery charging power, noting that 15% more energy is required for charging than will be available for discharging.
- Annual Energy Production is the number of MWh produced by plants at projected utilization.
- CRF is the Capital Recovery Factor which spreads the upfront capital cost of building and decommissioning the power plant over its lifetime of N years given a cost of capital r , specific to the country/investor:

$$CRF = \frac{r(1+r)^N}{(1+r)^N - 1}$$

It is important to consider that normal return on investment equal to the cost of capital is included in the LCOE cost. Therefore, in a perfect world investors should continue investing until prices captured by their investments (Capture prices) fall to the point where price equals LCOE. If the LCOE is lower than the capture prices, this means that there is room for more investors to come to the market.

Table 1: LCOE comparison for the Bulgarian market

Generation Type	Old NPP	New NPP	Coal	CCGT	PV	Wind	BESS
Installed power LTM (MW)	2,032	-	3,400	-	4,270	700	2h
Capacity Factor (CF)	85%	90%	30%	30%	16%	22%	1 cycle
Capex in €/kW – Local ¹	-	10,275	-	1,100	480	1,400	120
Capex in €/kW – Lazard	-	10,275	-	1,207	990	1,600	350
Variable cost in €/MWh ²	12	15	121	99	10	12	11
Fixed cost in €/MWh ²	170	120	45	35	15	25	5
Discount rate (r) ⁴	-	6%	-	10%	9%	9%	8%
Lifetime (years)	20	60	10	20	30	30	25
Capital recovery factor	-	0.062	-	0.117	0.097	0.097	0.094
LCOE / LCOS (€/MWh)	€35	€111	€138	€161	€53	€86	€56

Notes to Table 1: LCOE comparison for the Bulgarian market

I use actual costs whenever available. For the existing fully depreciated nuclear power plant (NPP), all costs come from published results and the calculated LCOE is consistent with the Regulator set recovery mechanism. ¹Capex for a new nuclear plant is the overnight cost of building a nuclear power plant based on recent publications in the Bulgarian press on the potential construction of 2 AP-1000 units targeting operation in 2035, adjusted for construction time. It is also the midpoint of the Lazard capex range for new nuclear power. The capex for the other technologies is based on actual projects deployed or considered for deployment in Bulgaria in 2025. PV and BESS capex is much lower than Lazard's projections due to the low duties on Chinese products (e.g., 2.7% for PV/BESS). ²Variable and fixed costs are based on regulatory market published data for current operators in the market. We add balancing costs for intermittent resources such as PV (€10/MWh) and wind (€12/MWh) due to the need to balance their output. CCGT variable cost is calculated at Eur 35/MWh gas cost and 58% efficiency factor but only 30% utilization (or capacity factor). The capacity factor for PV and wind is based on actual output observed in the country. New wind projects claim approx. 10-30% higher efficiency due to larger diameter blades, but this assumption has not been proven and is thus not utilized in this analysis. ³The variable cost for BESS is calculated as 15% x a charging price of €76 (LTM) = €11 which represents the losses in charging the battery. This gives us LCOS or the Levelized Cost of Storage for comparison purposes. In addition, in the model, we assume that charging volume is 15% higher than discharging volume. The LCOS always varies based on the charging price, so the value in the table above is only representative of the LTM average charging price of €76/MWh for one cycle. The charging price is calculated in the model dynamically. ⁴Cost of capital is based on available financing for renewables of 70% debt, 30% equity and 10% tax rate based on the WACC formula. The NPP cost of capital is lower due to government guarantees while the CCGT cost of equity is higher due to the uncertainty of the EU position on gas as a transition fuel and the potential short project life span.

The table above is compiled based on interviews with industry executives and publicly available data, some of which changes over time. For example, the EU CO₂ tax on carbon emissions, assumed at its current level of Eur 70/ton has varied in the past from €40 to over €100. If the carbon price increases, coal generation suffers the most as it emits 1.3 tons/MWh while gas suffers less as it emits 0.35 tons/MWh. Similarly, the CCGT LCOE is calculated on Eur 30/MWh gas price but gas prices in the EU have varied from €25/MWh to €50/MWh.

The marginal cost of electricity supply in Bulgaria is typically the cost of coal generation (as it is the only variable source that provides that last bit of supply when needed) or sometimes the marginal cost for energy imported into Bulgaria is typically the cost of gas generated electricity. There is a substitution effect between gas and coal generation. This is of secondary importance to me in this analysis because my main objective is to minimize coal generation (or

more broadly fossil fuel generation) with greater use of renewables. Whether fossil fuel generation comes from domestic coal or imported gas is important, but it is not the focus of this paper. It should be clear from the LCOE table above that the projected usage of a potential new CCGT plant is so low at 30% that its LCOE becomes significantly higher than coal (i.e., €138/MWh for coal vs. €161/MWh for gas).

3. Demand analysis

Energy demand in Bulgaria has been constant at 35 TWh annually. The main factors that influence demand are continued improvements in energy efficiency (e.g. replacement of resistive heating with air-conditioning or heat pumps), global warming (i.e. with the increase in average temperatures, air-conditioning demand in the summer increases while heating demand in the winter decreases), electrification of transport (additional energy demand from electrical vehicles or EVs) and new industry demand for AI data centers. EVs are flexible as they can be charged at night when nuclear power is plentiful or at noon when PV produces excess power while data center demand is typically baseload (i.e., constant throughout the day).

We estimate that EV impact on demand will be gradual. For example, there are about 62k vehicle registrations per year (passenger cars, vans, trucks) in Bulgaria. Assuming EVs reach 100% share of new registrations in 10 years, there will be $(62k \times 10 \text{ years} / 2) = 300k$ EVs in Bulgaria by 2035. Based on average km of 21k km/year, $250 \text{ Wh/km} \times \text{charging efficiency of } 80\%$, this will result in an additional annual energy demand of $300,000 \text{ EVs} \times 21,000 \text{ km} \times 250 \text{ Wh} / 80\% = 2.0 \text{ TWh}$ which is meaningful but not significant relative to total load.

Data center demand is potentially more significant, but data centers require baseload power. Bulgaria's only source of inexpensive baseload power is the existing nuclear power plant at LCOE of Eur 35/MWh. It is unlikely that the government owned plant will remove inexpensive energy from the market and push up consumer prices. Therefore, I conclude that data centers will develop jointly with new inexpensive baseload power, either generated in Bulgaria or imported. For these reasons, data center demand is not considered in this model.

Another factor is the variability of demand on a daily, weekly, and seasonal basis. Even if Bulgaria is self-sufficient on an aggregate annual basis (net exports represented only 5% of generated energy in LTM to June 2025), the picture is quite different on a daily/seasonal basis. The chart below shows demand, supply, and prices on LTM basis for the last 12 months:

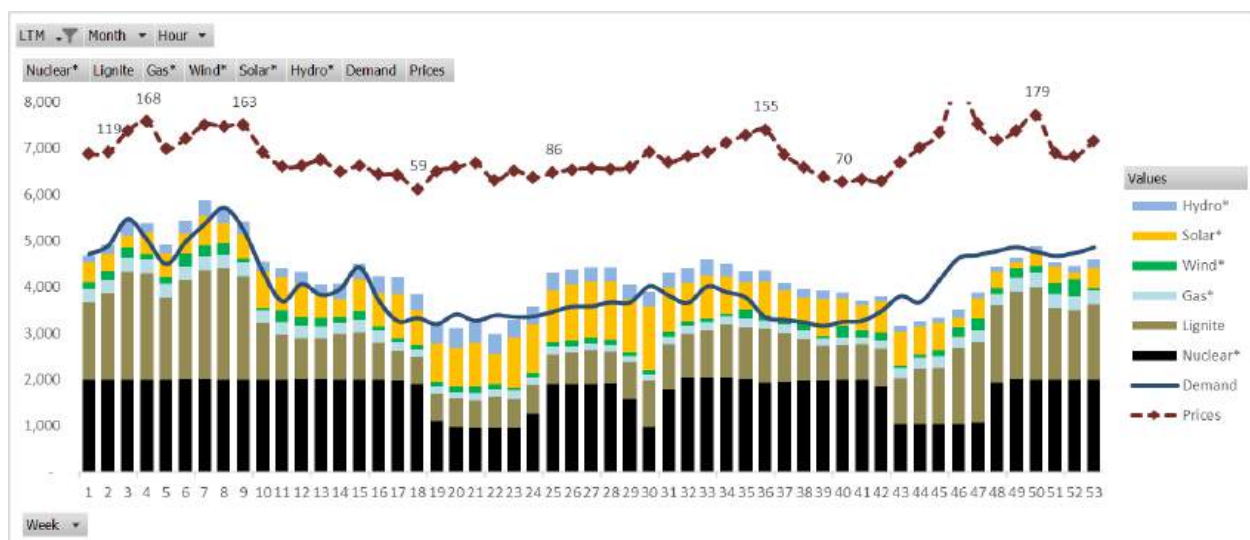


Figure 3: Demand, supply and prices on weekly basis, LTM July 2025

On a seasonal basis, it is evident from the chart that demand is significantly higher in the winter. Net exports are not explicitly shown on the chart, but they can be inferred from the demand (load) curve. Whenever generation is above load, the country exports electricity whereas the country imports electricity. The nuclear power plant maintenance outages are scheduled at times of lowest demand and highest hydro output (due to melting snow, weeks 19-24). However, if the maintenance window extends late into fall and wintry weather arrives, the coal plants are unable to ramp up generation quickly enough to cover the gap and the entire region becomes short on energy. This was the case in weeks 43-47, November 2024, when the government requested mothballed coal plants to restart.

This variability on a seasonal daily basis is even more extreme if we compare demand and generation on an average winter day and an average summer day. Figure 4 shows generation, demand and power prices for each hour, averaged in January, and Figure 5 shows the hourly averages in July:

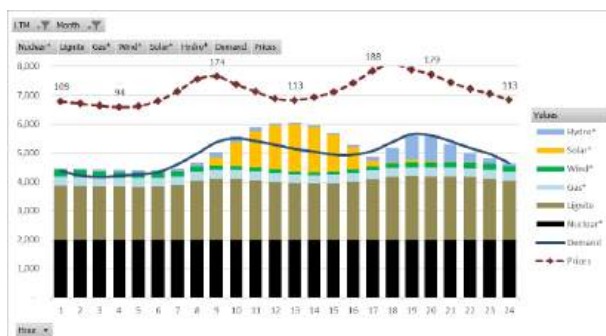


Figure 4: Average winter day generation

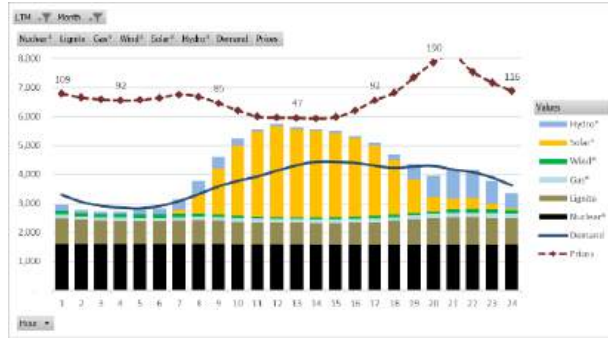


Figure 5: Average summer day generation

The PV contribution is small in the winter (8% of daily generation), and significant amounts of coal generation capacity are needed to meet demand in non-daylight times. Coal provides 41% of total winter demand in this case. Further, even small shortages of power, when demand exceeds supply around 8-9 am and 5-6 pm local time, lead to large increases in power prices. This means that in the winter, there is no spare generation capacity from the neighboring countries. Even if enough batteries are installed to shift the solar generation at noon to the evenings, there is simply not enough energy to be time-shifted (i.e., approx. 4 GWh available excess energy vs. coal generation of 48 GWh) to consider not running the coal plants in the winter.

4. Model Description

This is an Excel-based model with two main inputs: installed PV capacity and installed BESS capacity. There is no timeline for completion, just an optimal end-state generation mix that is likely to be achieved in the next 3-5 years. Demand is held constant at 35.2 TWh annual energy consumed. The generation volume from nuclear, gas, hydro, and wind are also held constant. The historic generation data is sourced from energy-charts.com and cross-checked with published data. The model uses hourly data, split for the analysis in 12 months x 24 hours. It performs calculations on hourly data averaged over a month. The input data is for the last twelve months to the end of July 2025 (called “LTM”).

Global model assumptions

1. Exports are capped at 1.0 GW power in any given hour, consistent with current values.
2. Minimum coal capacity is one unit running at 140 MW for grid reliability purposes.

Modelling steps and intermediate assumptions

1. Average PV power installed for LTM 2025 is 4,270 MW (4.3 GW). This capacity at 16% capacity factor x the typical solar profile for Bulgaria gives the same energy output as the historic data for the period. Actual installed PV capacity was 3,500 MW in July 2024 and 4,700 MW in July 2025. For a given input of installed PV capacity,

the model calculates the new PV output for every hour based on an hourly PV generation profile. The charts below show the model impact if PV generation increases by ~50% to **6.5 GW** for the months of January and August, without coal and without storage. Even a 50% increase in PV will not help much in December (as there is a significant gap still to be filled up by coal), while this amount of PV will produce so much energy in July that most of it will need to be curtailed (or wasted, the red area). The presence of fixed nuclear generation that cannot be varied exacerbates this problem:

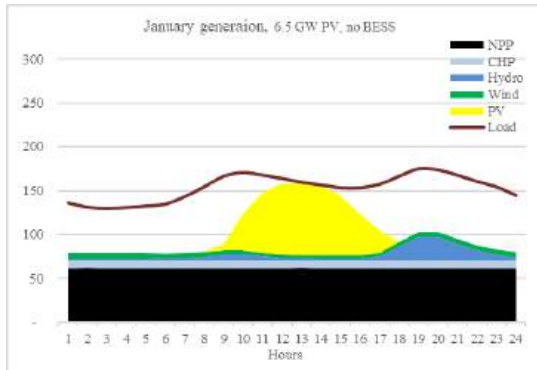


Figure 6: PV hourly at 6.5 GW in the winter

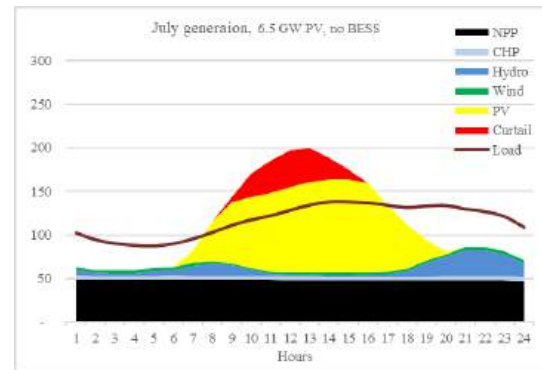


Figure 7: PV hourly at 6.5 GW in the summer

2. In this step, I calculate the actual gap between actual load and the actual generation from nuclear, wind, hydro, gas, and **modelled** PV generation. This gap is currently filled by coal generation.
3. Next, I calculate the desired amount of BESS capacity to flatten the gap above fully by taking the difference between the value of the gap for a given hour (for each month) and the average value of the gap across the hours of the day. Negative values indicate excess energy that should be used to charge the BESS if available. Positive values indicate the need to discharge the batteries. The desired amount of BESS capacity varies by month and is highest in the summer.
4. Next, we plot the actual hourly LTM prices, in Eur/MWh to determine battery cycles:



Figure 8: Actual LTM prices, simple hourly average over LTM

Based on the observed prices, the BESS can operate on 2-cycles today. In the morning cycle, the prices are lower due to the fixed output of the nuclear power plant against the reduced night-time demand. The evening cycle or the PM cycle is the typical cycle induced by the high PV output at noon vs. the higher evening peak demand. However, it turned out that modelling two cycles is complicated and unnecessary. As more PV is installed, the prices at noon become so low that it would be more advantageous to charge the batteries at noon and then discharge them partially in the evenings and sometimes the following morning. Therefore, I am modelling only one cycle per day, but the available batteries are charged at the lowest price as computed by the model (it could be at night or at noon) and discharged at the highest price.

5. Next, we take the installed BESS capacity and spread it out in the same proportion to the desired capacity to flatten the gap. The chart below illustrates the case for the month of August with 4.3 GW of PV (no change from today) and 4.5 GWh of BESS capacity. Negative values indicate charging, positive values discharging.

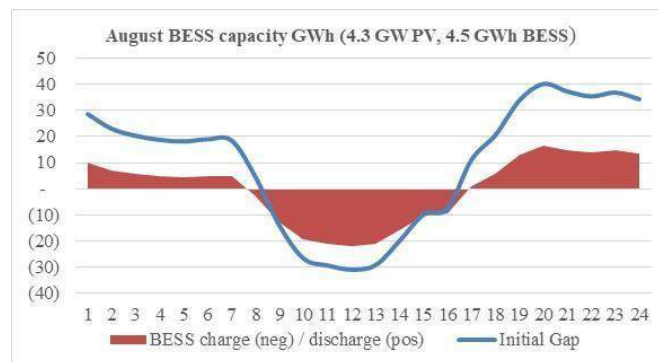


Figure 9: Illustration of BESS distributing PV energy over 24h. We have not made the decision whether installing 4.5 GWh of BESS capacity is economically justifiable. The model only says more BESS is needed to flatten the curve.

6. Next, following the spreading of energy across the day, incl. there required 15% higher volume to charge the batteries vs. what is discharged, we fill up the rest of the gap with coal. If coal is not needed (e.g., in the summer, if enough PV and BESS are available to flatten the curve), then we set a minimum coal output of 1 unit (140 MW) for system stability purposes. Then we check if exports exceed our export power limit of 1.0 GW per hour. In any hour where this limit is exceeded, the PV output is curtailed.
7. Next, we model the impact of the volume changes on the capture prices (the average market price earned by a generator) in two steps:
 - a. Increased PV output reduces prices in the same proportion to the volume of increased PV generation. The actual formula is (the sum of generation from all sources in the LTM case) / (sum of generation from all sources including the new PV / BESS installed capacity). This is a linear price adjustment that can be justified by the fact that PV has negligible marginal cost.
 - b. The second price adjustment component is to compute the price change due to the use of BESS to flatten the curve. Here we use the same approach as in capacity modelling, we take the difference in price for each hour from the average price across all hours and reduce this difference proportionately to the ratio of installed BESS to desired BESS. If the installed BESS is equal or higher than the desired BESS amount to flatten the gap, the price curve becomes completely flat, equal to the daily average price. Furthermore, if the BESS is significantly higher than the desired BESS, it could lower the prices below average. However, this is a two-edged sword: if too much BESS floods peak periods, prices can fall as far as zero. This is good for consumers, but detrimental to producers. Thus, we must find an optimal balance:

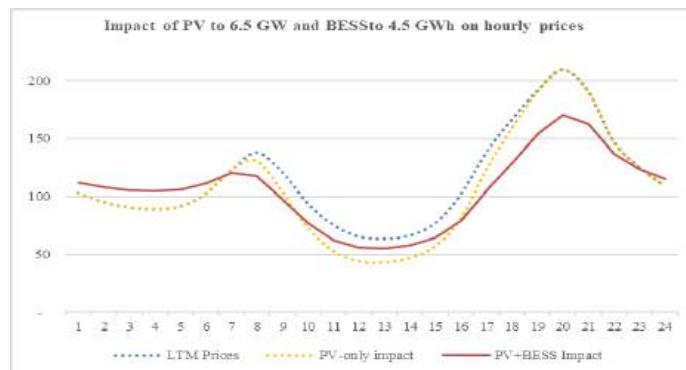


Figure 10: Example of price changes due to higher PV and BESS

8. Next, we calculate the weighted average capture prices for each generation source and compare these to the recalculated LCOE of PV and BESS. The PV LCOE is impacted by curtailment, while the BESS LCOE is driven by the charging price. Then we calculate the ratio of the capture price to the LCOE as a percentage change. If this percentage is higher than 0%, this means that the installed amount of capacity generates positive, excess returns for the investors, so they will continue to invest.
9. The output of the model is the CO₂ emissions reduction, calculated as the amount of needed coal to plug the gap x 1.3 tons of CO₂ per net and the total price to consumers, calculated as the weighted average price of all generation sources x their capture price. The capture price is the generation of each source x the calculated price. Typically, nuclear, a baseload generator will have a capture price remarkably close to the simple average of the prices, while PV will have lower capture prices due to much of its output being at noon when there is excess generation. The consumer price is typically above the simple average price because consumption of electricity (load) is weighted towards the evening hours. Below is a table comparing LTM capture prices to a model run with 6.5 GW PV and 4.5 GWh BESS:

Table 2: Prices per power generation type

Prices/MWh	Nuclear	Coal	CHP	Hydro	PV	Wind	BESS	Load
Actual								
LTM actual	€116	€159	€121	€142	€73	€121	€153	€121
LCOE actual	€35	€138	€120	€45	€53	€86	€131	€85
Return (price/LCOE)	233%	15%	1%	216%	<u>38%</u>	41%	<u>29%</u>	<u>42%</u>
Model Test Run								
Modelled prices	€106	€161	€112	€124	€58	€113	€134	€110
Modelled LCOE	€35	€138	€120	€45	€56	€86	€105	€86
Excess Return	204%	16%	-7%	175%	<u>3%</u>	32%	<u>27%</u>	27%

The actual LTM average price is €116/MWh, equal to the nuclear capture price. The average load price is higher at €121 because consumers need more energy in the evenings, when prices are higher. The excess returns for both PV and BESS are high, 38% and 29%, respectively. The excess return on the load (or the consumers) is 42%. We want the excess return (or the premium that consumers pay over the cost of generation in the hours they purchase electricity) to be as low as possible. **In the proposed model test run** with 6.5 GW PV and 4.5 GWh BESS, the consumer price has fallen to €110/MWh, the PV margin has decreased as the price is lower due to BESS charging, and the cost is higher due to curtailment. The excess return of PV is now only 3%, which means investment in PV is near its limit, while the system still needs more BESS with its positive excess investor return of 27%.

10. While evaluating the model, I noticed that using coal as a plug is not entirely realistic. The optimization routine in Excel would charge the BESS from any source, including coal if the margins are positive. The model would boost coal output at noon in the winter (when PV is not enough to charge the batteries), then reduce coal immediately. This is not possible with coal plants as discussed with industry executives. Coal plants typically vary output <35% of maximum power. I introduce another constraint in the model, where coal output must stay relatively constant, where the maximum power cannot exceed the average power by more than 35%. Below is an example of the constraint. The second case, with 44% variability where coal output drops close to zero at noon and then ramps up, is not physically possible.

11.

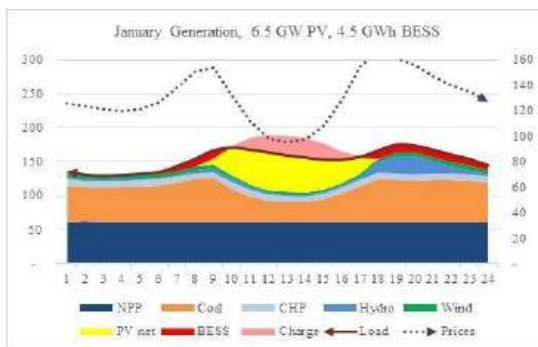


Figure 11: January output, coal variability 25%

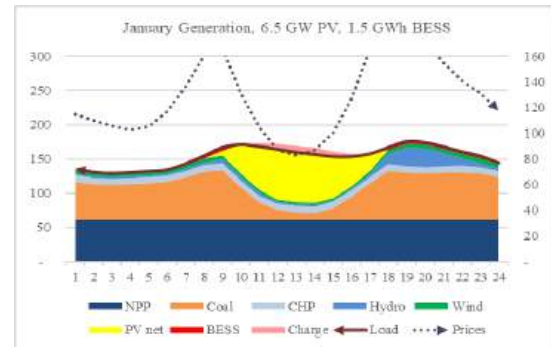


Figure 12: January output, coal variability 44%

12. Lastly, we introduce the benefit of a government capex subsidy scheme for BESS deployment. The currently announced subsidy is 40%. We model this by reducing the LCOE of BESS by the corresponding amount.

Utilization of the model

The model can be used either by inputting various installed capacities for PV and BESS, then observing the results or by using the Solver tool in Excel that varies the inputs until it meets our constraints and target criteria. We constrain investor returns to be positive for both PV and BESS and target either minimum CO₂ emissions or consumer benefit:

- A. Set CO₂ reduction target to -40%, with positive investor returns for PV and BESS
- B. Minimize consumer prices, positive returns, subject to coal variability limit
- C. Minimize consumer prices, positive returns, with BESS subsidy
- D. Minimize consumer prices, positive returns, with subsidies, relax variability and exports

Table 3. Model Output by Scenario

Model Inputs	LTM	Sc. A	Sc. B	Sc. C	Sc. D
PV installed base (GW)	4.3	6.7	7.8	7.8	8.5
Installed BESS (GWh)	0.5	5.0	13.2	13.2	20.6
Max export power (GW)	1.0	1.0	1.0	1.0	2.0
Coal variability limit (<35%)	35%	24%	35%	35%	112%
BESS capex subsidy	0	0%	0%	40%	40%
Model Results					
PV Excess return (Price / LCOE)	38%	0%	0%	0%	0%
BESS excess return (Price / LCOE)	17%	15%	4%	16%	11%
PV curtailment (%)	-1%	-8%	-2%	-2%	0%
Net energy exported (GWh)	35	568	1,750	1,750	2,547
Required coal generation (GWh)	8,787	6,780	6,357	6,357	6,188
CO2 emissions vs. 2019 (-40% target)	-22%	-40%	-44%	-44%	-45%
Benefit to consumers					
Consumer wholesale price (Eur/MWh)	€ 121	€ 108	€ 104	€ 104	€ 103
Consumer wholesale price reduction	0%	-10%	-14%	-14%	-15%
Consumer benefit vs. LTM (Eur m)	€ -	€ 433	€ 588	€ 588	€ 639

The LTM case is a representation of the last twelve months. Both PV and BESS are attractive, max exports limit is 1 GW, there is minimal PV curtailment. The CO₂ emissions are at 22%, well below the target. Note, that is the scenario, the coal output limited to the minimum required domestically, i.e., to fill the gap in the model. Hence, the net exports are 35 GWh. In the actual LTM data, coal was running in the winter to support exports and therefore the net exports were closer to 2 TWh.

- A) In scenario A I target CO₂ emissions reduction of 40%. Excess returns for PV + BESS are set to be positive, then we look for a solution with the Solver tool. The optimum solution is for PV to increase to 6.7 GW, supported by 5.0 GWh of BESS storage. It should be noted that more BESS supports more PV and vice versa. Consumer prices will be 10% lower, which is a significant benefit. This is a likely scenario for Bulgaria in the 2026-27 period.
- B) In scenario B I switch to targeting the lowest possible consumer price, which also minimizes emissions. The model suggests a 14% in consumer prices can be achieved with 42% reduction can be achieved if PV increases to 7.8 GW PV supported by 13.2 GWh BESS. CO₂ emissions are 44% lower and **consumer benefit is €588m**. Note that in both scenario A and B, BESS investors enjoy excess returns, while PV excess return is 0 (equivalent to just meeting the cost of capital).
- C) In scenario C I introduce the 40% capex subsidy program that improves the investor business case for installing more BESS. The additional BESS should allow more PV to be installed but this turns out not to be the case as the batteries are saturated – i.e., we can speak of BESS curtailment at this point. The impact of the BESS subsidy is only to increase the already positive investor return in BESS. This is our optimal scenario, since the capex subsidy has already been announced and is expected to be distributed and it

indicates that other things being equal investors should first invest in more BESS, then in more PV.

- D) In scenario D I relax certain constraints, such as removing the coal variability constraint (for example, if we fill the gap with imported energy generated from gas, which does not have the variability constraint) and increasing max export power to 2.0 GW per hour. This is not a realistic scenario today, because increasing the export limit requires investment in infrastructure and it also depends on how much PV and BESS the neighboring countries will install but it is a useful scenario to consider what would be possible in the absence of the constraints. The results are not significantly different from scenario C. PV increases slightly to 8.5 GW, BESS to 20.6 GWh and consumer prices decrease by 15%. It is difficult to justify this scenario that involves removal of major constraints for a minimal improvement in prices.

5. Evaluation of results

Scenario C is the best outcome as it exceeds the CO₂ reduction target, it is based on current costs and state of technology and results in a significant consumer benefit of €588m. I could not reduce coal output further with any combination of the inputs. My assessment of the core limitation of energy generation in Bulgaria is that the PV output varies on a seasonal basis (determined by the geographic position of the country), whereas the electricity demand variation is driven by the heating needed in the winter. BESS helps even out the peaks, but it only shifts supply during the day, not between seasons if its impact is partial. Changing the heating mix for the country (i.e., heating with gas as in Western Europe) is a slow process and difficult to justify without further analysis. However, if the recent trend of warmer winters and hotter summers continues, the demand will change where more energy will be needed in the summer due to more air-conditioning and less in the winter. This will improve the business case for more PV.

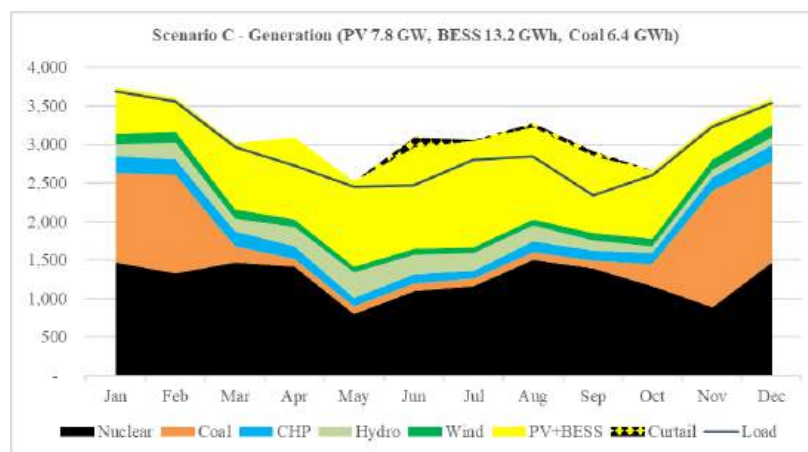


Figure 13. Scenario C. Model output of total generation, PV at 7.3 GW and BESS at 12.8 GWh. The yellow area is PV generation which is split into 55% direct consumption, 43% BESS charging and 2% curtailment.

Coal generation requirement

Coal generation of around 6 TWh is needed in the preferred scenario C. Furthermore, this generation is concentrated in the winter months with average power (over 30 days) of 2.2 GW. While this power can be supplied either by domestic coal or gas generated electricity imports, it is important that Bulgaria can meet this requirement on its own. Therefore, the summary of Figure 13 is that Bulgaria needs a fossil fuel resource with max power around 2.2 GW that is only used for four months and then it is not needed at all.

Replacement of coal with gas generation

To provide this power with a CCGT (or an open cycle gas turbine), we need to calculate the expected capacity factor for this new installation. Assuming 2.5 GW installed power, the utilization will be $(4 \text{ months} \times 2.2 \text{ GW}) / (12 \times 2.5 \text{ GW}) = 29\%$. This is not sufficient to justify the cost of a new CCGT as its LCOE will be Eur 162/MWh which is significantly higher than the cost of coal generation. A private investor will not consider a free market, <30% capacity factor for any gas generation technology.

Nuclear power

As discussed in the modelling section, Bulgaria needs more flexible resources to address the seasonal misalignment of demand with the high seasonal variability of PV generation at our geographic latitude. Adding more fixed, non-variable generation sources increases the floor in the summer which results in higher curtailment for PV. While new nuclear installations offer variable output power (unlike the currently installed Kozlodui reactors), nuclear power has extremely high upfront costs and low variable costs, so a reduction in output will increase the LCOE significantly.

Comparing Bulgaria (with 40% nuclear generation) to the only country in Europe with higher nuclear penetration, France (with 65% nuclear generation), we note that France is well interconnected to countries with high gas generation share that is flexible. In Bulgaria, CCGTs represent a small share of the total regional generation. Looking at the summer months, where the model suggests that demand is <2,500 GWh per month from May to September (from Figure 13), nuclear power is providing 1,500 GWh on average during those months. An additional reactor will add 800 GWh to the mix, leaving little room (only 200 GWh) for all the other generation sources.

Therefore, I believe that additional nuclear power should only be considered as a replacement of the existing capacity (projected to be needed in 2047/2049) or if coupled with AI data center installations (but then it is unlikely that the energy cost will be competitive) or as a

replacement for neighboring countries coal plants' (there is 3 GW of constantly running coal capacity in Serbia that would need to be replaced at some point in the future).

Wind power

Wind generation is not in scope for this study as no wind projects have been deployed in the country in the last five years. There are two key issues: 1) Bulgaria has weaker wind resources than neighboring countries as evidenced by the average existing wind farms' capacity factors of 22-23% and 2) grid connections to the few windy areas are non-existent. However, the model does suggest that wind offers positive investor return and therefore wind should be considered in future updates to the model.

6. Limitations of the analysis

There are potential improvements to the model, starting with using average generation data for the last three years, instead of LTM; a more sophisticated way to model the price decline due to PV penetration and others. I do not believe such optimizations will change the model results significantly. My goal was to create a model to find the optimum generation mix analytically and this goal is met. Future users of the model can adjust parameters to their reasoning (for example, gas price evolution, CO₂ emissions price evolution, interconnect capacity, LCOE for different technologies, etc.) but still benefit from the generation mix optimization routine.

7. Conclusion

The results of the model suggest that scenario B and C are equivalent and support the conclusion that the energy system in Bulgaria has the capacity to absorb 7.8 GW of PV and 13.2 GWh of total BESS installations. Subtracting the currently installed capacities, we project around 3 GW of new solar installations and 13 GWh of BESS installations in the next 3-5 years. Both PV and BESS are required to be able to drive the CO₂ emissions reduction to below 40% in the next 2-3 years. These results are based on a set of conservative assumptions such as flat demand (any increase in demand will open space for more capacity), self-sufficiency where Bulgaria can meet its winter peak with coal generation at about 6 TWh annual production (any substitution of coal generation with imports will reduce CO₂ emissions even further) and current technology costs.

What does it mean for investors?

Expect positive investment returns assuming PV is built below €480k/MW and BESS below €120k/MWh. The returns for BESS appear to be slightly higher than the returns for PV but the optimal approach is to build PV+BESS.

What does it mean for coal?

Coal generation can be minimized but cannot be eliminated. Around 2.2-2.5 GW of coal capacity must be available in selected months, although the average annual utilization will be below 30%. Coal plant operators must prepare for seasonal operations with or without government support.

Learnings from the modelling exercise

Creating a comprehensive energy system model is complicated and is always based on a set of assumptions. I achieved my goal in creating a simple and interactive model that can be easily verified and optimized. Future users of the model may add their own assumptions about the slope of the decline in prices or the costs of renewables for each individual investor and for the industry. Adding wind to the model will be a simple exercise if so desired by a potential future user. For me, it was a great learning opportunity, and I am looking forward to updating and further assessing the model in the future.

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From Pre-Seed to Scale: Comparative Analysis of Venture Capital Ecosystem Conditions Supporting Startup Growth in Kazakhstan and Selected Global Regions

By Karima Bizhanova

Abstract

This study investigates why nearly 86% of early-stage startups in Kazakhstan stagnate at the pre-seed level, despite recent growth in the national venture capital ecosystem. It examines how institutional design, investor behavior, and structural bottlenecks influence the trajectory from pre-seed to scalable growth. A comparative analysis is conducted between Kazakhstan and select global regions - including the Middle East and North Africa, Southeast Asia, Europe, and the United States - using a mixed-method approach that integrates funnel analysis, policy benchmarking, and ecosystem maturity scoring. Data are drawn from national startup activity records, investor materials, regional capital market reports, and semi-structured interviews, addressing the near-total absence of qualitative research capturing founder and investor experiences in this context. The research proposes the Venture Progression Grid as an original conceptual model.

Findings show that startup growth is constrained by limited exit opportunities, lack of investor syndication, and underdeveloped later-stage funding mechanisms. In contrast, peer ecosystems have leveraged sovereign investment models, staged funding continuity, and diverse deal structures to promote scale. The research highlights how informal norms, founder capacity, and institutional incoherence intersect to restrict growth in Kazakhstan. It concludes with policy and ecosystem-level recommendations focused on strengthening executional accountability, enabling gender inclusion, and fostering investor-founder alignment.

Introduction

In the global discourse on entrepreneurial ecosystems, the dynamics of early-stage venture formation in emerging markets remain markedly underexplored. Kazakhstan - despite its strategic location, resource wealth, and ambitious state-backed innovation initiatives - continues to exhibit a persistent pattern of startups stalling at the pre-Series A stage. This phenomenon is not merely anecdotal; it reflects a systemic bottleneck with far-reaching implications for the region's capacity to sustain innovation-driven growth.

Yet, a significant gap persists in the scholarly record. To date, only a single substantive quantitative investigation exists, most notably the macro-level work of RISE (2025) - which, while valuable, is oriented primarily toward institutional structures and state policy interventions. Absent from the literature is a robust body of qualitative research capturing the lived experiences of founders and investors, as well as comparative analyses situating Kazakhstan within broader regional and global venture capital (VC) ecosystems.

This absence of multidimensional inquiry leaves critical questions unanswered. How do founders perceive and navigate the early-stage funding landscape in Kazakhstan? What behavioral patterns and structural constraints shape investor decision-making? And how do these

local dynamics compare to those in more mature or capital-dense ecosystems, such as the Middle East and North Africa (MENA), the Association of Southeast Asian Nations (ASEAN), Europe, or the United States?

To address these questions, this study employs a mixed-methods design that integrates semi-structured qualitative interviews with founders and investors, comparative ecosystem benchmarking, and a critical review of existing academic literature. This approach enables not only an examination of early-stage stagnation mechanics but also an exploration of the broader interplay between capital availability, investor psychology, and entrepreneurial ambition.

Building on preliminary observations from ecosystem stakeholders and grounded in established theory on venture finance in emerging markets, we advance the following hypotheses:

- **H₀:** Kazakhstan's early-stage startup stagnation is driven primarily by the behavioral conservatism of local investors, who favor low-risk, revenue-first ventures concentrated in traditional sectors.
- **H₁:** Kazakhstan's early-stage startup stagnation stems chiefly from founder-related factors, including limited entrepreneurial experience, low propensity to scale internationally, and insufficient strategic growth orientation.
- **H₂:** The stagnation of Kazakhstani startups at early stages is primarily attributable to constrained global market access, limited human capital, and weak institutional support structures, rather than investor psychology alone.

By positioning these hypotheses in direct contrast, this study seeks to move beyond policy rhetoric and isolated performance metrics, offering a grounded, ecosystem-level perspective capable of informing both academic understanding and actionable intervention. In doing so, it establishes one of the first scientifically rigorous, industry-informed foundations for venture capital research in Kazakhstan, a field still nascent even within the global scholarly landscape, and opens wide empirical and conceptual pathways for future investigation.

Literature Review

In constructing this literature review, we prioritized sources that examine Kazakhstan's innovation and venture capital ecosystem through both institutional and actor-level lenses. Our selection includes a mix of academic studies, development reports, and data-driven analyses that reflect the evolving nature of the country's entrepreneurial landscape. Foundational policy-oriented works (e.g., Nauryzbaeva et al., 2024; ADB, 2022; Sadyrova et al., 2021) were chosen for their insight into Kazakhstan's state-driven innovation strategy, its global benchmarking efforts, and the legal-institutional architecture that underpins its current ecosystem. We also included comparative and theoretical studies (e.g., Yılmaz, 2012; Welter et al., 2003) that offer broader regional and structural context, as well as highly empirical and actor-focused reports such as RISE Research (2025), which provide the most comprehensive startup-level data available. These works were particularly valuable for understanding the

behavior of investors, the limitations of early-stage capital formation, and emerging gender dynamics within the ecosystem.

However, across this body of literature, several consistent research gaps emerge. Many studies remain largely descriptive, macroeconomic, or policy-focused — lacking insight into startup team dynamics, investor-founder interactions, and commercialization pathways. There is limited analysis of how informal norms (such as gender stereotypes or risk aversion) shape decision-making, and few works apply behavioral finance or testable hypotheses grounded in real founder experiences. Additionally, gender disparities are often acknowledged but rarely explored through intersectional or structural lenses. This research aims to address some of these gaps — particularly those related to investor psychology, institutional coordination, and gender inclusion at the early stages of startup development. Other gaps — such as the long-term impact of digital platforms, the role of diaspora capital, or the effectiveness of existing support mechanisms—are identified as future opportunities for continued academic and policy exploration.

RISE Research (2025) delivers a comprehensive, data-driven analysis of the evolving venture capital (VC) landscape in Central Asia, with a detailed national chapter on Kazakhstan. Drawing on 200+ startup surveys, 40+ investor interviews, and proprietary deal data, the report captures the maturity gradient, structural frictions, and capital formation dynamics in the region. It represents the most empirically grounded account of VC in Kazakhstan to date.

The report outlines the growth of Kazakhstan’s VC market from \$12M in 2018 to \$71M in 2024, reflecting a ~35% average annual growth rate. Pre-seed and seed deals dominate (60% and 26%), while late-stage capital remains scarce. SAFE agreements account for 63% of investment instruments, signaling a preference for speed and flexibility in early-stage transactions. Despite progress, nearly 50% of all deals are undisclosed, highlighting persistent transparency gaps.

The analysis reveals systemic bottlenecks including a lack of follow-on funding, limited LP liquidity, and low risk appetite among institutional investors. However, capital efficiency is emerging in key verticals such as AI, HealthTech, and Enterprise Software, with AI experiencing a 213% year-on-year increase in deal value. Moreover, startups launched by Kazakhstani founders abroad (e.g., UniBlock, Atarino) are increasingly leveraging international accelerators such as Plug and Play, Draper University, and Alchemist, while retaining operations in Central Asia.

Critically, the report explores gender dynamics for the first time at this scale. Women account for only 7% of total VC funding in 2024 and comprise 20% of startup co-founders and 18% of VC fund managers. Paradoxically, women-led startups raised higher average pre-seed checks (\$281K vs. \$207K) than male-led ones, with an 86% pre-seed success rate - challenging investor assumptions and supporting arguments for gender-lens investing in frontier markets.

Methodologically, the report applies funnel analysis (318 pitch decks, 5 investments), sector-level segmentation, valuation benchmarking, and return expectation modeling (average IRR: 30.8%, pre-seed money multiple: 8.7x). It integrates both qualitative and quantitative data,

positioning it as a critical empirical benchmark for further academic research on emerging VC ecosystems. However, this research lacks an analysis of cause and effect relationship, that is, it does not address deeply why startups remain at early-stage.

Nauryzbaeva et al. (2024) explore the development of Kazakhstan's innovation ecosystem through a macro-institutional and comparative policy lens. The study focuses on the evolution of state-led innovation strategies, highlighting milestones such as the 2021 Presidential Decree on “Building a Diversified and Innovative Economy,” the National Development Plan, and the Concept of Digital Transformation for 2023–2029. The authors analyze Kazakhstan's relative position in global indices, most notably the Global Innovation Index—where the country ranks 68th in innovation inputs but lags at 87th in outputs, illustrating inefficiencies in innovation conversion.

The paper draws on cross-national comparisons with the U.S., EU, South Korea, and China to assess best practices in state-driven innovation support. Kazakhstan's grant-based support mechanisms are examined through the lens of a ten-year program that allocated over 13.3 billion tenge to 324 projects. The authors also propose integrating the Boston Consulting Group's innovation pyramid and the Higher School of Economics (HSE) index methodology to assess innovation readiness at both national and regional levels.

Methodologically, the study employs correlation and regression analysis to explore the relationship between digitalization indicators and innovation metrics. The findings suggest strong correlations between digitalization and variables such as the volume of innovative products and internet access, while paradoxically identifying a negative correlation with internal R&D expenditures in ICT.

Although the paper introduces conceptual tools such as the MUIS (Mechanism for Managing the Innovative Environment of an Enterprise), the focus remains largely macroeconomic and descriptive, with limited insight into startup dynamics or commercialization outcomes. Nonetheless, the study provides a structured foundation for understanding the policy architecture surrounding innovation in Kazakhstan and outlines priority sectors such as MedTech, AgriTech, and GreenTech.

The 2022 ADB report offers a comprehensive macro-level policy analysis of Kazakhstan's venture capital (VC) ecosystem, positioning itself as a diagnostic tool for legislators and ecosystem architects. The study traces the legal, institutional, and economic reforms following the 2018 amendments to the Law on Investment and Venture Funds (LIVF), outlining both systemic challenges and actionable policy recommendations across the financing, legal, IP, and university innovation domains.

A key strength of the report lies in its comparative lens: the authors contextualize Kazakhstan's VC trajectory with models from Israel, Singapore, and the U.S, emphasizing the importance of legal harmonization, IP commercialization, and flexible audit frameworks. The report also articulates a nuanced understanding of Kazakhstan's post-Soviet investment culture, particularly the state's dominant role and the difficulties of reconciling entrepreneurial risk with state financial control.

In sum, while the ADB report represents a valuable state-level policy snapshot, it offers limited traction for understanding the dynamic, actor-driven processes that shape startup creation, scaling, and failure. Future research must adopt a multilevel, actor-inclusive approach - combining institutional, economic, and sociocultural dimensions - to inform more equitable and sustainable VC ecosystem design in Kazakhstan.

Shakirtkhanov (2017) examines the role of venture funds as one of the key sources of financing for innovative entrepreneurship in Kazakhstan, primarily from a macro-level perspective, with a focus on institutional aspects. The study emphasizes the state as the main initiator and investor in the venture infrastructure (particularly through the activities of the former National Innovation Fund and NATD), the implementation of public-private partnership models, the adoption of international experience (e.g., the U.S. and Israel), and the launch of Kazakhstan's first local venture funds (such as Sentras, Areket, and others). However, the author does not address the micro-level analysis of startups themselves — their teams, motivations, and growth barriers. The work also lacks any gender analysis, does not explore the causes of startup stagnation at the pre-seed stage, and offers no assessment of the effectiveness of existing programs and investment funds. The data used primarily covers the period before 2015, which limits its relevance in the context of digital transformation and the emergence of new market players. Therefore, further research should focus on expanding the empirical base, collecting data from real ecosystem participants (founders, accelerators, investors), studying the mechanisms of transition from pre-seed to growth stages, and analyzing the policy and economic conditions necessary for the development of an independent, inclusive, and sustainable venture capital market in Kazakhstan.

Sadyrova et al. (2021) analyze the development factors of innovation processes in Kazakhstan through a macro-institutional lens, emphasizing the role of government policy, global benchmarking, and systemic inefficiencies in the commercialization of innovation. The authors frame innovation as both a national economic imperative and a response to structural challenges in the Kazakh economy, where growth via traditional extractive industries has reached its limits.

The study integrates data from Kazakhstan's performance in the Global Innovation Index (ranking 74th in 2020, up from 79th in 2018), correlating it with GDP fluctuations and the quality of institutional mechanisms for innovation management. The authors categorize global innovation models into three national types: R&D-centric (e.g., U.S., U.K.), environment-facilitating (e.g., Germany, Sweden), and infrastructure-coordinated (e.g., Japan, South Korea), arguing that Kazakhstan remains in the early stage of forming its own model, relying heavily on state regulation and public policy instruments.

Sadyrova et al. propose a multi-stage framework for analyzing innovation, incorporating statistical regression between GDP and innovation rank, and present a typology of innovation (product, process, organizational, marketing). They offer strategic recommendations ranging from improved coordination between business and state to fostering scientific infrastructure and innovation-oriented education.

However, the analysis remains predominantly descriptive, focused on macroeconomic and policy-level mechanisms. While the study articulates a broad policy agenda, it does not empirically assess the success of specific programs or provide micro-level insights into startup ecosystems, team dynamics, investor behavior, or gender inclusion in innovation processes

Methodology

This study adopts a mixed-methods research design to deeply investigate the venture capital (VC) ecosystem in Kazakhstan and broader Central Asia (CA), while also conducting comparative analyses with more mature ecosystems in MENA, Europe, the United States, and ASEAN. The combination of qualitative and quantitative methods allows for a nuanced understanding of region-specific barriers and opportunities, while situating these within global trends and structures.

Given the nascent and under-researched nature of the Central Asian startup and VC landscape - particularly in Kazakhstan - a qualitative approach was essential to capture the depth, complexity, and socio-political specificity of founder and investor experiences in this region. We conducted semi-structured interviews with stakeholders, incorporating insights from over 20 senior executives representing venture funds, accelerators, incubators, and related ecosystem organizations. Given their leadership positions, responses often reflected not only individual perspectives but also institutional positions or the collective experience of their organizations.

- Founders of startups at the MVP, seed, and early growth stages
- Venture capitalists and angel investors active in Kazakhstan and CA: ActivatC (Activate C)/ EA Ventures (EA Group)/ Astanahub Ventures / Eurasian Hub Ventures/ Big Sky Capital /Silk Road Innovation Hub
- Accelerator and incubator managers based in Astana Hub/ AIFC/ NURIS (Nazarbayev University)/ MOST Business Incubator / MOST Ventures/ ABC Incubator (NU)/ Qonaev Hub/ Terricon Valley/ Red Team Accelerator
- and private platforms
- Policy influencers and ecosystem builders from regional development institutions

We selected these individuals based on their proximity to funding decisions, policy shifts, and founder support systems. Priority was given to those with direct exposure to bottlenecks in early-stage growth, as they offered firsthand insight into stagnation trends, gender disparities, and investor biases. Snowball sampling was used to reach less visible actors such as first-time founders outside the capital, enabling a more representative picture of the ecosystem.

The semi-structured format allowed flexibility to explore emergent themes - such as informal investor networks, founder credibility perceptions, and regulation ambiguities - while ensuring that core comparative dimensions (e.g., investment stages, exit paths, and policy influence) were covered.

In addition, quantitative methods and document analysis were applied to international

comparisons due to limited direct access to stakeholders in MENA, EU, U.S., and ASEAN ecosystems. Over 70 reports, datasets, and scholarly publications were analyzed, including regional capital flow data (e.g., PitchBook, Crunchbase), ecosystem benchmarks (e.g., Global Innovation Index, OECD), and policy white papers (e.g., ADB, BCG, MassChallenge).

These sources were systematically coded across five core variables that shaped our comparative analysis:

1. Market size and scalability potential
2. Exit activity, including IPOs, acquisitions, and secondary markets
3. Funding stages and deal structures, with attention to risk appetite and instrument diversity (e.g., SAFEs, equity rounds)
4. Policy support and regulatory frameworks
5. Founder mindset and entrepreneurial culture, particularly regarding risk-taking, global vision, and resilience

These variables were selected to isolate not only structural features of venture ecosystems but also cultural and behavioral patterns that explain early-stage stagnation in Kazakhstan. For example, while ~60% of deals in Kazakhstan are publicly disclosed, investor conservatism and founder hesitation to scale internationally continue to limit growth beyond pre-seed. In contrast, more mature ecosystems demonstrate continuity across these five dimensions, enabling smoother transitions from ideation to Series A and beyond.

The mixed-methods design allowed us to balance local depth with international context. While qualitative interviews illuminated the actor-level frictions behind startup stagnation in Kazakhstan, the comparative lens provided empirical reference points and policy innovation pathways. This methodology ensures the research is both grounded in lived realities and actionable through global insight.

All interviews were conducted in compliance with ethical research standards. Participants were informed of the study's goals and granted informed consent. Personal data were anonymized, and all identifying details are kept confidential.

Developing Venture Progression Grid conceptual model

Building upon the empirical insights derived from our mixed-methods investigation of the Kazakhstani startup ecosystem, we sought to move beyond descriptive analysis and design a conceptual instrument capable of capturing the dynamics of entrepreneurial progression. Specifically, we developed the Venture Progression Grid (VPG) as an original framework for assessing how early-stage ventures navigate systemic barriers and why so many remain locked in pre-scalability phases. Our intention was not merely diagnostic; we aimed to contribute to the advancement of venture studies both within Kazakhstan where systematic models of entrepreneurial progression are virtually absent and in the broader field of comparative innovation research. By formalizing the interaction of institutional, behavioral, and financial-structural obstacles into a reproducible model, we sought to provide scholars, policymakers, and practitioners with a rigorous tool for evaluating venture dynamics across

contexts. In this sense, the VPG functions as both a conceptual innovation rooted in Kazakhstan's unique ecosystem realities and a transferable analytical device that can enrich global debates on startup progression, funding bottlenecks, and the conditions of venture scalability.

In the course of our research design, we considered several potential frameworks through which to conceptualize the systemic stagnation of early-stage ventures in Kazakhstan. One option was to construct a founder–investor trust matrix, emphasizing the interpersonal dynamics of credibility, negotiation, and perceived risk tolerance. While this approach offered insight into a single dimension of the entrepreneurial journey, it proved analytically insufficient in light of the evidence we collected. The interviews and document analysis consistently revealed that stagnation is rarely attributable to relational frictions alone; rather, it emerges from the compounded effect of institutional deficiencies, behavioral constraints, and structural gaps in financing.

This recognition led us to abandon more reductionist models in favor of an integrative framework capable of capturing multi-level interactions. The Venture Progression Grid (VPG) thus emerged as the most appropriate tool, precisely because it allows us to map how barriers intersect and reinforce one another across successive stages of startup development. Unlike a unidimensional trust matrix, the VPG reflects the dialectical nature of venture progression: even when one barrier is partially mitigated (for example, an investor-ready founder), advancement may remain blocked if institutional exits or downstream funding mechanisms are absent. In this sense, the VPG aligns more faithfully with our empirical findings, offering a dynamic and holistic representation of venture evolution that can accommodate the complexity of real-world entrepreneurial ecosystems.

The Venture Progression Grid (VPG) is organized along two primary axes:

- X-axis (Stages of Startup Development): Idea/Pre-MVP, MVP/Pre-seed, Proof of Concept, Early Traction (Seed-A), and Growth/Scale. These stages trace the canonical pathway of venture evolution, from ideation to scalable expansion.
- Y-axis (Barrier Domains): Institutional, Behavioral, and Financial-Structural. These three barrier types represent systemic constraints that recurrently surfaced in our empirical research:
 - *Institutional Barriers*: deficiencies in legal protections, exit infrastructure, and regulatory clarity.
 - *Behavioral Barriers*: trust asymmetries, founder-investor mindset misalignments, and cultural risk aversion.
 - *Financial-Structural Barriers*: scarcity of funding vehicles, absence of follow-on capital, and underdeveloped deal structures.

Unlike reductionist frameworks that privilege a single dimension (e.g., financing availability or founder competence), the VPG explicitly foregrounds the *interaction* of these domains. This enables a multi-layered mapping of venture constraints, recognizing that no

barrier operates in isolation.

The VPG functions by tracing how the three categories of barriers converge and compound across the developmental trajectory of a startup. At each stage:

- Pre-MVP: Institutional uncertainty (e.g., grants and taxation), combined with behavioral immaturity (“hackathon” mentality) and financial disorganization (absence of angel capital, chaotic use of SAFEs), creates an unstable launch environment.
- MVP: Even where founders begin to professionalize, weak IP protection and opaque accelerator mandates undermine progress. Behavioral deficits (inability to pitch effectively, investor distrust) are mirrored by the lack of structured follow-on capital.
- Pre-seed: Bureaucratic hurdles in accessing state programs, poor due diligence practices among founders, and an absence of structured rounds collectively impede maturation.
- Early Traction (Seed-A): Startups face a “lock-in zone,” where institutional absence of exit mechanisms (e.g., IPOs), founder fear of scaling or equity dilution, and the nonexistence of serial capital converge to block further progress.
- Growth/Scale: Even successful ventures encounter team turnover, divergent visions, and a vacuum of late-stage investors, leading to systemic fragility.

The mechanism is inherently dialectical: barriers are not additive but interactive. A reduction in one dimension does not guarantee progression if complementary conditions in the other two remain absent. For example, an investor-ready founder (behavioral barrier mitigated) may remain trapped without downstream capital or institutionalized exit opportunities.

We can make a simple illustration of the model via tabular form (see Table 1).

Table 1. Venture Progression Grid Structure

Startup Stage	Institutional Barriers	Behavioral Barriers	Financial-Structural Barriers
Pre-MVP	Uncertain grant access; ambiguous tax environment	Lack of investor orientation; “hackathon-style” mentality	Fragmented seed instruments (SAFE chaos); absence of angel networks
MVP	Weak IP protection; unclear role of accelerators	Inability to pitch effectively; distrust toward external capital	Lack of follow-on funding; nominal VC support
Pre-seed	Bureaucratic hurdles in obtaining state support	Weak due diligence capacity	Absence of structured investment rounds
Early Traction (Seed-A)	Absence of exit mechanisms; IPOs infeasible	Fear of scaling and equity dilution	Nonexistence of Series A capital; lack of serial investors
Growth/Scale	Institutional fragility; high team turnover	Divergent founder–investor visions	Absence of late-stage capital pools

It can be used to formalize scoring for each barrier type at each stage of startup development. We can also illustrate the scoring rubrics in the next Table 2.

Table 2. Venture Progression Grid Scoring rubrics

Barrier Type	Score = 0 (Absent / Low)	Score = 1 (Mild)	Score = 2 (Moderate)	Score = 3 (Severe / Lock-in)
Institutional	Clear regulatory framework; state support predictable; exits exist (IPO, M&A)	Minor bureaucracy; some ambiguity in policy; exits rare but possible	Frequent bureaucratic hurdles; unclear or inconsistent support schemes; no local IPO pathway	No exit mechanisms; grants misaligned with VC logic; heavy bureaucracy or policy vacuum blocks scaling
Behavioral	Founders investor-ready (pitching, scaling, due diligence); investors show risk appetite & trust	Skills gaps appear sporadically (some weak pitching or limited trust) but not systemic	Widespread skill deficits (most founders can't pitch / navigate due diligence); investors risk-averse	Deep mistrust of external capital; hackathon-style mindset dominates; systemic lack of scaling literacy
Financial-Structural	Full capital ladder (angels, seed, A, B+) present; diverse & standardized deal structures (SAFE, equity, convertibles)	Some gaps in capital continuity (e.g., weak follow-on funding) but most deals still structured	Few follow-on options; chaotic deal terms (SAFE misuse, unstructured rounds); funds too small for scale	Severe cliff after seed; absence of angels; no Series A/B funds; total capital fragmentation

VC Ecosystem Comparison. Central Asia VS Other Countries

A close reading of the most current empirical evidence - including the RISE Research corpus for 2023–2025 - together with comparative literature on emerging and mature innovation markets, reveals key differences between three distinct typologies of venture capital ecosystems. These ecosystems diverge in structural depth, competitive dynamics, and institutional maturity, offering differentiated risk-return profiles for capital allocators and founders alike.

To situate Kazakhstan's venture ecosystem within a broader context, we conducted a comparative assessment across four regions: MENA, ASEAN, Europe, and the United States. These ecosystems were selected because they represent different stages of venture capital maturity, from frontier (MENA, ASEAN) to advanced (Europe, U.S.). This comparative lens allows us to distinguish which barriers in Kazakhstan are truly systemic and which reflect the natural growing pains of a young market. By structuring the analysis along five dimensions — ecosystem size and growth, exit activity, funding stages, policy support, and founder–investor mindset — we aim to produce a holistic benchmark rather than isolated contrasts.

The comparison reveals that while Kazakhstan exhibits rapid early-stage growth, its ecosystem is disproportionately concentrated at pre-seed and seed phases, with limited progression beyond. In contrast, MENA and ASEAN have engineered mechanisms of capital continuity, Europe benefits from pan-regional policy harmonization, and the United States

remains unrivaled in depth and scalability. The table below synthesizes these findings, making visible both Kazakhstan’s strengths — such as dynamic early-stage activity and growing state support — and its persistent weaknesses in exits, deal structuring, and alignment between founders and investors.

Table 3. VC Ecosystem Comparison by dimensions

Dimension	Central Asia	MENA	ASEAN	Europe	United States
Ecosystem Size & Growth	Small but fast growth (\$12M → \$71M, 2018–2024), concentrated at early stage	Growing with sovereign LP capital (UAE, KSA) and state-backed funds	Rapidly expanding, regional hubs (Singapore, Jakarta), cross-border VC flows	Mature, diverse hubs (Berlin, Paris, Nordics), slower growth but stable	Largest globally; \$200B+ annually, deep capital pools
Exit Activity	Virtually absent (no IPO/M&A track)	Simulated exits via sovereign wealth funds, some IPOs (Tadawul)	Active regional IPOs and M&A in Singapore, Indonesia, Vietnam	Moderate IPO and acquisition markets, pan-European M&A common	Strong IPO/M&A pipelines (NASDAQ, NYSE, tech giants acquire startups)
Funding Stages	86% stuck at pre-seed/seed, Series A+ nearly missing	Early-stage + growth supported by sovereign funds; Series B+ possible	More balanced, Series A–C common, VC–PE continuum forming	Well-distributed from seed to late-stage, though less risk-tolerant	Full capital ladder: pre-seed to mega-rounds
Policy Support	Strong signaling (grants, accelerators, Astana Hub) but weak execution, bureaucratic gaps	Heavy state involvement, sovereign LPs ensure continuity	Targeted incentives, government co-investment in Singapore/Malaysia	EU-wide funds, startup visas, regulatory sandboxes	Limited direct policy, but deep market institutions, strong private LP base
Founder–Investor Mindset	Founders grant-dependent, weak scaling literacy; investors cautious, misaligned	Founders ambitious, but ecosystems highly state-shaped	Founders increasingly global-facing, investors pragmatic	Professionalized founders & investors, trust-based norms	High-risk appetite, founder–investor alignment strong, culture of serial entrepreneurship

Results & Discussion

Why do startups in Kazakhstan not go beyond the early stage?

Drawing upon over 30+ in-depth interviews with founders, investors, incubator operators, and venture professionals - augmented by comparative regional data and institutional perspectives - this study identifies a tripartite set of structural inhibitors that collectively account for the stagnation of early-stage ventures in Kazakhstan. These barriers are not episodic or incidental but systemic in nature, shaping the behavior and decision-making of both entrepreneurs and capital allocators. Crucially, the three primary bottlenecks - founder mindset, investor logic, and post-MVP capital gaps - are interlocking, and were presented by stakeholders in a consistent hierarchy of perceived impact.

1. Founder Mindset: Strategic Narrowness and Operational Gaps

The dominant barrier to startup scalability in Kazakhstan is not technical capacity but strategic limitation at the founder level. Many early-stage teams demonstrate impressive technical skills yet struggle with the entrepreneurial competencies required for building scalable enterprises such as market discovery, internationalization, and capital-efficient growth.

A striking majority of founders frame their ventures through a local problem-solving lens, targeting products–market fit exclusively within Kazakhstan or, at most, the broader Central Asian region. Consequently, practices such as cross-border user validation, iteration against global performance benchmarks, and culturally adaptive market testing remain rare. This geographic and cognitive narrowness imposes structural limits on scalability from inception.

Even among technically proficient teams, operational fluency in modern startup methodologies, lean iteration, product–market fit feedback loops, traction modeling, and strategic talent acquisition is inconsistent. Founders often fail to pivot in response to weak or ambiguous market signals and underprepare for fundraising processes that require alignment with institutional capital standards. As a result, ventures that appear promising at the prototype or MVP stage frequently plateau due to avoidable execution risks.

Moreover, attributes recognized in global entrepreneurship literature as predictors of venture success resilience, interdisciplinary collaboration, and long-horizon strategic orientation (see Eisenmann, Ries, & Dillard, 2013; Blank & Dorf, 2020) remain underdeveloped across most first-time founding teams in Kazakhstan. This deficit appears both generational and infrastructural: founder training programs rarely extend beyond basic incubation curricula, and the pool of experienced operator–mentors within local accelerators is limited.

Taken together, these patterns provide strong empirical confirmation of Hypothesis 1: Kazakhstan’s early-stage startup stagnation is rooted in founder-related factors, specifically limited entrepreneurial experience, a low propensity to pursue international scaling, and insufficient strategic growth orientation. The evidence demonstrates that these constraints operate not as isolated weaknesses but as mutually reinforcing limitations, systematically constraining the trajectory from prototype to scalable enterprise.

2. Investor Behavior: Outdated Habits and Misjudged Risk

The second major constraint arises from investor behavior that remains out of sync with high-growth venture logic. While Kazakhstan has seen a growing presence of angel investors and family offices in the startup space, most still operate with approaches inherited from traditional business settings.

Rather than adopting a portfolio mindset that balances risk across multiple early-stage bets, many local investors prioritize control, cashflow predictability, and collateral-backed security. As a result, investment decisions tend to favor short-term returns over long-term upside, with demands for excessive equity stakes (40–60%) at the pre-seed stage - eroding cap table integrity and reducing future investability.

Compounding this, limited familiarity with modern venture instruments - such as SAFE notes, convertible equity, and structured founder vesting - often produces deal terms that are structurally unattractive or even unworkable. This makes it difficult for local startups to pass due diligence from international VCs, regardless of the underlying product quality.

At a deeper level, there is a persistent mispricing of risk. Local capital often treats uncertainty as unreliability, underestimating the value of experimentation in early-stage company-building. In this environment, founders are discouraged from pursuing bold, globally competitive opportunities.

Collectively, these findings confirm Hypothesis H₀: Kazakhstan's early-stage startup stagnation is significantly driven by the behavioral conservatism of local investors, who favor low-risk, revenue-first ventures rooted in traditional sectors, thereby constraining the growth trajectory of potentially scalable companies.

3. Capital Gaps: Structural Vacuum Between MVP and Series A

Even when early-stage teams demonstrate traction, Kazakhstan's capital markets offer limited support beyond the MVP milestone. The funding pipeline is weighted toward grants, accelerators, and pre-seed checks often capped at \$50-100K. Yet, once ventures require \$500K-\$2M in catalytic capital to operationalize growth through sales, hiring, or international expansion they encounter a systemic void. This directly disproves Hypothesis H₂: while founders in more mature ecosystems, such as the United States, can access substantial growth-stage capital domestically, Kazakhstan lacks comparable pools altogether.

This gap is not a function of absolute capital scarcity. Several national initiatives including public funds-of-funds and regional VC vehicles exist in principle. However, in practice, risk aversion, bureaucratic disbursement processes, and minimal coordination with international capital pools render these resources ineffective at scale.

The consequences are predictable and widespread: ventures with real market traction are forced to bootstrap beyond sustainable limits, dilute excessively to uninformed early investors, or exit prematurely through local acqui-hires. Many capable teams migrate abroad, contributing to an incipient but growing founder diaspora, a trend that further weakens local ecosystem compounding effects.

While comparative analysis highlights Kazakhstan's relative immaturity in exits and

downstream capital compared to MENA, ASEAN, Europe, and the U.S., it also reveals an ecosystem in motion: early-stage activity is vibrant, but progression falters beyond seed. To capture this dynamic more precisely, we developed the Venture Progression Grid (VPG) — a framework that maps how institutional, behavioral, and financial-structural barriers accumulate across startup stages. The heatmap below visualizes this lock-in pattern, showing both the points of entry and the bottlenecks that constrain scale

Table 4. Heatmap illustrating the compound effect of barriers

Barrier type/Startup stage	Pre-MVP	MVP	Pre-Seed	Early Traction	Growth/Scale
Financial-Structural barriers	1	2	2	3	3
Behavioral barriers	1	2	2	2	3
Institutional Barriers	1	1	2	2	3

Practical Recommendations

Systemic Interactions: An Ecosystem-Level Lock-In

Critically, these three bottlenecks - founder capability, investor behavior, and post-MVP financing - do not operate independently. Instead, they interact to produce a reinforcing equilibrium of stagnation:

- Under-trained founders accept predatory terms,
- Legacy investors reinforce short-term thinking,
- Capital gaps within Kazakhstan's scale punish even well-executed ventures.

Each player, acting logically on their own, ends up reinforcing a system that works poorly for everyone. Without bigger structural changes, small fixes in one area (e.g., founder training) are likely to be cancelled out by problems in another (e.g., financing norms).

To enable a next-generation startup pipeline capable of scaling beyond national borders,

Kazakhstan must rewire key parts of its venture infrastructure:

1. Founder Track Redesign

- Move beyond generic incubation toward deep venture education.
- Partner with global accelerators, research labs, and operator-mentors to embed experiential learning in venture building building on existing models already underway in

Kazakhstan, such as collaborations between Nazarbayev University's Astana Business Campus and StartX at Stanford University.

- Leverage the growing presence of international university branches in Kazakhstan as regional hubs for accelerator partnerships and venture ecosystem linkages.
- Promote founder secondments into scale-up environments abroad (e.g., Southeast Asia, CEE, MENA).

2. Investor Upskilling and Syndicate Structuring

- Establish national training programs in venture finance for emerging investors.
- Encourage the formation of syndicates and micro-VCs that operate under standardized term sheets and international best practices.
- Provide co-investment incentives conditioned on adoption of venture-compatible instruments (e.g., capped SAFE).

3. Catalytic Capital Innovation

- Develop milestone-based post-MVP funds (public-private hybrid) with automatic follow-on eligibility tied to growth metrics.
- After the first step, to call for Kazakhstan-originated startups from abroad to return to Kazakhstan
- Pilot revenue-based financing and equity-free seed mechanisms to support non-linear founders.

Research Limitations and Future directions

While this study provides a comparative lens on Kazakhstan's venture capital (VC) ecosystem drawing insights from founders, investors, and policy frameworks across multiple regions, it remains bounded by several methodological and thematic constraints:

1. Gender-Lens Exclusion (Deliberate Scope Limitation)

Initially, the study intended to explore gender-based disparities in startup formation, fundraising, and ecosystem navigation, particularly the experiences of women entrepreneurs in Kazakhstan and neighboring post-Soviet markets. However, due to limitations in representative sampling and data depth, this dimension was excluded from the core analysis to preserve empirical rigor. Rather than offering fragmented or anecdotal observations, this decision reflects an intentional narrowing of scope to maintain methodological coherence. That said, this exclusion is not a dismissal of the issue's significance - on the contrary, the gender lens represents a critical frontier for future research.

Three foundational studies underscore the importance and complexity of gender dynamics in entrepreneurial ecosystems:

- Welter et al. (2003) demonstrate that formal equality under the law often fails to override deeply embedded informal norms - such as patriarchal cultural scripts or family expectations - that shape women's entrepreneurial behavior in post-Soviet economies.

Their institutional duality framework highlights how formal reforms can be neutralized by cultural inertia, making gendered entrepreneurship a multidimensional and historically contingent phenomenon.

- Abouzahr et al. (2018) reveal a stark funding paradox: women-led startups, despite securing less capital, generate higher revenue per dollar invested. Their empirical analysis attributes this disparity not to founder competence but to latent investor biases and structural bottlenecks. While U.S.-focused, their findings suggest a fertile basis for replicative research in emerging markets with different socio-economic logics, such as Central Asia.
- Martínez and Nguyen (2014) explore how ICT tools can serve as enablers for women entrepreneurs across Central Asia, particularly in overcoming time poverty, mobility constraints, and access to finance. However, their report remains limited in theoretical grounding, intersectional granularity, and post-2013 relevance - indicating a need for updated digital gender inclusion research post-COVID and amid AI-driven platform shifts.

Together, these studies justify why future inquiry into women's participation in the Kazakhstani VC landscape should be anchored in updated, contextually grounded, and intersectional frameworks.

2. Temporal Limitations and Market Dynamism

Given the rapid evolution of early-stage capital markets - particularly under the influence of geopolitical shocks, AI integration, and sovereign wealth fund activism - the data collected in this study may become rapidly outdated. The VC landscape is highly non-stationary; investment theses, sectoral bets, and regulatory frameworks shift over months, not years. Longitudinal data, cohort tracking, and real-time deal-flow analytics are necessary to sustain relevance over time.

3. Sampling Bias and Access Asymmetry

Despite efforts to ensure regional and stakeholder diversity, the study faced limitations in accessing certain founder cohorts - particularly those operating outside the capital city or beyond government-affiliated incubators. This introduces an unavoidable urban and institutional bias. Similarly, data from investor syndicates were often opaque due to NDAs or informal deal structures, limiting the transparency of some investment pathways.

To deepen and expand the academic utility of this study, we identify three under-explored but high-potential directions for future research:

1. Founder Migration and Transnational Opportunity Flows

A systematic investigation of founder migration - both brain drain and boomerang return - can illuminate the push-and-pull dynamics that shape Kazakhstan's startup exodus. Are

founders leaving due to capital constraints, regulatory frictions, or lack of market scale? What distinguishes those who return or stay engaged with the home ecosystem remotely? Studying diaspora-led ventures, exit patterns, and cross-border startup funding flows could yield valuable insights into global-local entrepreneurship dynamics.

2. Evaluation of Co-Investment Schemes and Public Capital Instruments

With the emergence of sovereign VC funds, match-funding platforms, and quasi-governmental co-investment programs in Kazakhstan and similar ecosystems, there is a pressing need to rigorously evaluate their effectiveness. Do these mechanisms catalyze additional private investment, or merely crowd out organic capital formation? Experimental or quasi-experimental designs, including randomized rollouts and comparative policy analyses, could enhance the evidentiary base.

3. The Role of Diaspora Microphones and Narrative Capital

Diaspora founders, influencers, and public intellectuals often act as narrative amplifiers - shaping how emerging markets are perceived by global capital. Exploring how “diaspora microphones” construct or contest venture legitimacy can offer new ways to understand soft power within VC ecosystems. This research would integrate media studies, political sociology, and entrepreneurship - bridging narrative theory with capital flows.

Conclusion

In acknowledging these limitations and highlighting future directions, we position this study not as a definitive map, but as a provocation - a call for interdisciplinary, empirically grounded, and justice-oriented exploration of Kazakhstan’s evolving venture capital terrain. Addressing gender equity, founder mobility, and co-investment efficacy is not merely academically desirable, but existentially necessary if the country aspires to build an inclusive and globally relevant innovation economy.

Kazakhstan is not lacking in entrepreneurial energy, technical depth, or institutional effort. But without a coordinated evolution of founder development, investor alignment, and capital maturity, the system risks chronic underperformance - locked into cycles of under-scaled ambition.

Recalibrating this trajectory will not require massive new infrastructure (like those that is being built in Alatau, former Gate City), but rather smarter configuration of existing assets and a shared understanding that building a globally competitive venture ecosystem is a long-term, compounding process. With the right design, Kazakhstan can transition from an early-stage startup pipeline to a true scale-up engine - positioned to lead in Central Asia and compete across emerging global markets.

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The Effects of Sun Exposure on Skin Health: A Comprehensive Study on the Relationship between Ultraviolet Radiation, Dermatological Conditions, and Skin Cancer Risk

By Ariya Deshmukh

1. ABSTRACT

Ultraviolet (UV) radiation, a component of sunlight, plays a dual role in human health, contributing to vitamin D synthesis while also posing significant dermatological risks. This review explores the biological effects of UVA, UVB, and UVC radiation on the skin, emphasizing their roles in common skin conditions such as sunburn, photoaging, and actinic keratosis. Furthermore, it examines how chronic UV exposure can lead to skin cancers, including basal cell carcinoma, squamous cell carcinoma, and melanoma, highlighting associated risk factors. Through an evaluation of current research, the article underscores the mechanisms by which UV radiation damages DNA and disrupts cellular regulation. It also stresses the importance of early sun protection to mitigate long-term health risks. This review aims to inform and engage a young audience on the scientific and public health significance of UV exposure.

2. INTRODUCTION

While the sun plays an integral part in maintaining a healthy body — providing the skin with vitamin D to assist in normal bone function and health — it can also cause damage. Sunlight travels to Earth in ultraviolet waves of different lengths, with the length of the UV waves affecting how deeply the rays penetrate an individual's skin. These ultraviolet rays can be dangerous, resulting in sunburn and damaging skin cell processes. However, the skin has some mechanisms to prevent this: the topmost layer will constantly shed dead skin cells to replace them with healthy ones (“Sun and”). Still, certain risk factors, including genetics, can cause long-term damage, such as skin cancer. Skin cancer occurs when UV rays harm the DNA in skin cells, leading to rapid growth and division and thus causing tumors. The best way to reduce the harmful effects of the sun is to limit sun exposure; this entails staying in the shade, covering up with clothing, and putting on broad-spectrum sunscreen that minimizes and filters out UV rays (“Sun Safety Facts”). Moreover, the best time to start sun protection measures is during childhood, when young ones can learn healthy sun exposure habits. The implications of sunlight deserve to be explored further and brought to the attention of all generations. The essay sets out to provide a comprehensive study of the relationship between ultraviolet radiation, dermatological conditions, and skin cancer risk and to describe the importance of sun protection measures and awareness campaigns.

3. UNDERSTANDING ULTRAVIOLET RADIATION

3.1. Ultraviolet radiation and its sources

Ultraviolet radiation is a non-ionizing form of radiation, meaning it is composed of oscillating electric and magnetic fields traveling at the speed of light (“Non-Ionizing”). Due to the

range of their wavelengths, UV waves are divided into three categories: UVA (315-400 nm), UVB (280-315 nm), and UVC (100-280 nm), as seen in Figure 1.

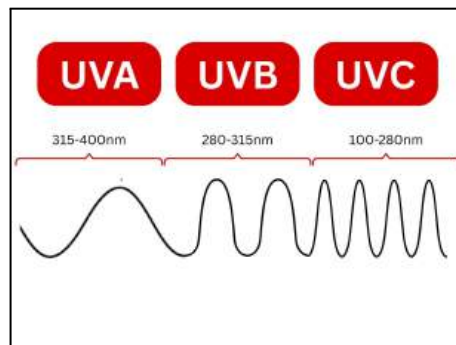


Fig 1: The three types of ultraviolet waves and their wavelengths.

3.2. The different types of ultraviolet radiation

As mentioned above, UV rays are divided into three categories according to their wavelength. UVA rays have the longest wavelength of 315-400 nm and are the most common form of ultraviolet radiation, with them making up 90-98% of the UV rays in terrestrial sunlight (Khan et al.). Moreover, UVA rays are one of the strongest forms of ultraviolet radiation, being able to penetrate glass, windows, and cloud cover. They maintain the same level of strength during the daytime throughout the year, increasing exposure. Hence, UVA rays are strong enough to penetrate the skin deeper than other forms of ultraviolet radiation; they are able to go into the dermis, or middle layer of the skin, which transports nutrients and produces sweat, along with hair (Khan et al.). When they penetrate the dermis, UVA rays can result in genetic damage to cells. As a result, the skin will attempt to prevent further damage by darkening or tanning and can even result in sunburn; over time, exposure to high amounts of UVA radiation will result in premature skin aging or wrinkling (photoaging). Compared to other forms of ultraviolet radiation, UVA rays are less prone to causing skin cancer. However, they still play a part in the development of cancerous activity. With the help of UVB rays, UVA radiation can damage the DNA in skin cells and produce mutations that can lead to skin cancer.

UVB rays have a shorter wavelength than UVA rays (280-320 nm), but they are still not the shortest or highest energy in the ultraviolet radiation spectrum. UVB rays typically do not penetrate as deeply into the skin and only reach the epidermis, or the top layer of skin (Khan et al.). In addition, it is important to note that contrary to UVA rays, UVB rays only make up 5% of the sun's ultraviolet rays that reach the skin (D'Orazio et al.). However, this does not mean that they are less dangerous than UVA rays. By targeting the epidermis, UVB rays are responsible for sunburns and play the largest role in causing skin cancers, including melanoma; they are capable of damaging DNA and triggering mutations that will result in abnormal growth of skin cells and ultimately form malignant tumors ("What is the").

UVC rays have the shortest wavelength and highest frequency of ultraviolet radiation, consequently making them the most dangerous. Nevertheless, fortunately, UVC rays *cannot* penetrate the Earth's atmosphere. UVC is completely blocked by the ozone layer because when these rays reach the stratosphere, they are absorbed by oxygen molecules (O_2) in the atmosphere. UVC rays will then split these molecules into atoms (O), which will react with other oxygen molecules to produce ozone (O_3) in the atmosphere ("All"). Even so, humans can still come into contact with UVC rays through artificial means. Sources such as lamps or lasers sometimes contain UVC, which can cause skin burning and photokeratitis, or eye injuries. For dermatological conditions, UVC presents a very low risk since its penetration depth is very low — it only reaches the outermost layer of the epidermis (Khan et al.).

3.3. Overview of how ultraviolet radiation interacts with the skin

The skin is divided into three layers: the epidermis, dermis, and subcutaneous fat (Figure 2). The epidermis is the thin, outer layer of skin, consisting of squamous cells (which constantly shed), basal cells (which are found under squamous cells and at the base of the epidermis), and melanocytes (which make melanin and thus determine the color of skin). The middle layer of the skin is known as the dermis, a flexible and strong layer held together by the protein collagen. Containing hair follicles, nerves, and blood vessels — as well as lymph vessels, sweat glands, fibroblasts, and sebaceous glands — the dermis contains pain and touch receptors ("Anatomy"). Finally, the subcutaneous fat layer is the deepest, consisting of collagen and fat cells that help preserve warmth and absorb shock.

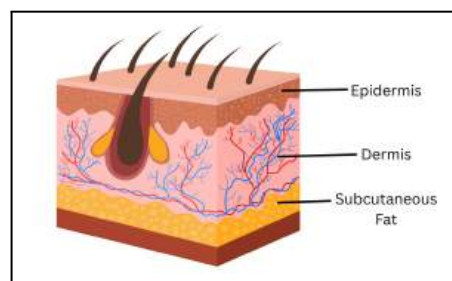


Fig 2: Structure of human skin layers, including the epidermis, dermis, and subcutaneous fat.

Too much exposure to ultraviolet radiation will ultimately damage the elastin fibers in one's epidermis, causing wrinkles, sagging, and stretchiness. When the ultraviolet radiation penetrates even deeper, there is an increased risk of it harming skin cells and damaging the DNA. DNA controls the nucleus of cells, telling the cell how to form and control the body. Because ultraviolet radiation targets the DNA of skin cells, the cells will begin to lose their orderly function, which leads to the uncontrolled growth of cells. As this abnormal growth contributes to cancerous cells, tumors will arise, either benign or malignant.

4. DERMATOLOGICAL CONDITIONS ASSOCIATED WITH SUN EXPOSURE

4.1 Sunburn

Sunburn is a reaction to excess UV rays, causing the outermost layer of skin to become inflamed and painful, hot to the touch. There are two types of sunburn, including first-degree (when UV rays penetrate the outermost layer of skin) and second-degree (when UV rays damage the middle layer, or dermis, of the skin) (“Sunburn: Causes”). Melanin protects the skin from UV rays, but as the melanin becomes unable to protect the skin from extensive UV damage, the topmost layer of skin cells — known as the keratinocytes — begin to attract immune cells in an attempt to fight off the DNA damage. However, this simultaneously causes the skin’s blood vessels to leak between the cells, and this extra fluid results in the red, hot, and swollen skin associated with sunburn (Soyer). Moreover, other cells might release chemicals that further damage weakened cells, triggering itchiness and blotchy skin. Blisters appear, indicating that the keratinocyte layer has been killed, and so the skin begins to peel, as is characteristic of most sunburns. This immune cell invasion can occur after a few hours from the initial exposure to ultraviolet radiation, and it reaches its worst 24-48 hours after (D’Orazio et al.).

Symptoms of sunburn appear within a few hours of prolonged sun exposure and will get worse 24-36 hours after the initial exposure; symptoms will usually reduce in around 3-5 days (“Sunburn”). Sunburn can affect any exposed parts of the skin, and areas covered by clothing may also experience symptoms if the fabric is too thin, still allowing UV rays to penetrate through. Symptoms of first-degree sunburn, when ultraviolet rays hit the epidermis layer of the skin, include hot skin, pain, swelling, and peeling of the skin. The skin may even become itchy, and it will look red/pinkish on lighter skin (sunburn is typically harder to see on darker-skinned individuals). People may also experience fatigue, fever, nausea, or a headache if the sunburn is severe (“Sunburn: Causes”). Symptoms of second-degree sunburn include more swelling, wet-looking skin, and white discoloration around the affected area. Blisters filled with fluid may also appear and break. One may feel confusion or dizziness, with severe sunburns causing people to become dehydrated and go into shock (“Sunburn: Causes”).

Sunburn treatment does not heal the skin but rather alleviates pain and prevents further damage from being done. To treat sunburn, one should take frequent cold baths and showers, avoiding harsh soaps and exfoliants. A bath with oatmeal or baking soda may go even further to stop the pain (“Sunburn: Causes”). Moisturizers are another resource to soothe the skin; light moisturizers that contain aloe vera or soy typically work best and do not cause any worsening reactions. It is best to avoid lotions that contain petroleum or benzocaine as they can trap heat, irritating the skin and worsening the sunburn. Hydrocortisone cream can be used if the sunburn is particularly painful (“Sunburn”). To lessen any swelling or discomfort, the patient may also take a nonsteroidal anti-inflammatory drug (NSAID), such as ibuprofen. Furthermore, when skin is sunburned, it attracts fluid to its surface, taking water away from the rest of the body; thus, to treat a sunburn, one should frequently drink water to avoid dehydration, which could worsen the pain (“Sunburn: Causes”). In the case of second-degree sunburn, when blisters appear, the patient must not pop the blisters to prevent the risk of infection. Severe blistering may require the patient to be given rehydrating fluids by their healthcare provider. Finally, as the sunburned skin begins

to heal, extra protection must be taken, such as wearing clothing that completely covers the skin and is loose enough not to rub against the aggravated skin. If possible, one should avoid the sun until the skin is completely healed (Macmillan).

Even though sunburn fades, the lasting effects can be very damaging. Repeated sunburns can cause premature aging, such as liver spots, wrinkles, sagging, freckles, red veins, and discoloration (“Sunburn: Causes”). Sunburns will also lead to an increased risk of skin cancer, causing precancerous skin lesions, which are rough patches on the skin. Sunburn can damage skin cells’ DNA, leading to abnormal cell growth and leading to skin cancers, such as melanoma (the most dangerous type). Five or more sunburns between the ages of five and twenty result in an 80% increased risk of melanoma and a 68% increased risk of other skin cancers (Macmillan).

4.2. Photoaging

Photoaging — also known as photodamage or solar damage — is the term used for when the sun prematurely ages the skin. UVA rays are most common when leading to photoaging since they reach the dermis (deepest layer of skin). Hence, they can damage cells, resulting in the excess production of matrix metalloproteinases (MMPs) in the skin. Because MMPs are responsible for degrading extracellular matrix proteins such as collagen, fibronectin, elastin, and proteoglycans, these proteins will be increasingly degraded (Pittayapruerk et al.). As the collagen becomes damaged, the skin will be incorrectly built, resulting in leathery and loose skin (“Photoaging”). UV radiation may also affect capillaries and cause the thinning of blood vessel walls. This will result in the appearance of blood vessels on the skin and cause the skin to bruise and bleed easily. Photoaging is primarily visible on an individual’s face, neck, hands, arms, legs, and upper chest — all areas most commonly exposed to the sun. As a result, this illustrates that while chronological (intrinsic) aging is predetermined by age and genetics, photoaging depends on the degree of sun exposure. Photoaging (extrinsic) aging is controllable and depends predominantly on external factors.

Symptoms of photoaging appear in one’s teens and early twenties, and these symptoms most commonly appear in areas most visible to the sun, such as the hands, arms, legs, shoulders, face, and neck. Symptoms of photoaging include wrinkles, thinner skin, and a loss of skin elasticity (“Sun-Damaged”). Pigmentation changes are another symptom, and they include melasma, freckles, liver spots, and idiopathic guttate hypomelanosis (“Sun-Damaged”). Melasma is characterized by light brown, dark brown, or blue-gray patches on the skin (“Melasma”). Epidermal melasma is dark brown and has highly defined edges, sometimes responding well to treatment; on the other hand, dermal melasma is light brown/bluish and does not respond to treatment. The most common form of melasma is mixed melasma, which sometimes responds to treatment (“Melasma”). Liver spots, also known as solar lentigines or age spots, are dark spots where melanin has been clumped. They do not have any painful symptoms and are relatively harmless. Finally, idiopathic guttate hypomelanosis involves white spots that appear on the arms and legs and are benign. Broken capillaries may also be caused as a result of photoaging. These are also known as telangiectasia and are small vessels on the nose, cheek, and neck

(“Photoaging”). The broken capillaries may cause lines or patterns on the skin, and they are usually harmless.

There are numerous treatments to combat photoaging, such as lasers. Laser skin resurfacing can remove the epidermis of the skin and heat the dermis to increase collagen production, thereby making the skin appear smoother and more evenly colored (“Laser”). Fractional carbon dioxide lasering is another method that uses microbeams of light that coagulate tissue and remove broken blood vessels, along with redness. This results in the growth of new, healthy skin as well. Chemical peels may also treat photoaging since a chemical acid, including trichloroacetic acid or glycolic acid, removes the epidermis to allow for the regeneration of new skin. Chemical peels help with discoloration, as they remove any brown spots, and they can help in creating smoother skin. Topical skin care products, with ingredients like vitamins C and E, also help with treating fine lines and evening out colors (“Photoaging”). Products such as retinoids or retinols encourage damaged skin cells to fall off so that new ones can be created and come to the skin’s surface. This will also stimulate the protein production of collagen to encourage bouncier and tighter skin (“Laser”). In the case of precancerous cells that appear, photodynamic therapy may be used to destroy these precancerous cells while leaving healthy cells alone. In this process, the skin is coated with a photosensitizer to make the precancerous cells more sensitive to light. Subsequently, red or blue fluorescent light is applied to the skin, thus activating the medication and destroying the precancerous skin cells. Noncancerous cells that create liver spots can be treated with cryotherapy, where liquid nitrogen is used to freeze the spots and remove abnormal tissue. The frozen skin will then freeze and peel off, allowing for the growth of new cells (“Sun-Damaged”).

4.3. Actinic Keratosis

An actinic, or solar, keratosis is a precancerous skin growth, involving dry and crusty patches of skin; with time, it may become hard and wart-like (“Actinic Keratosis - Diagnosis”). Actinic keratoses (AKs) are forms of photoaging and often appear as reddish spots that can sometimes be raised above the skin; thus, due to their texture and elevation, actinic keratoses can be diagnosed by touch. Moreover, they frequently form on areas highly exposed to the harmful ultraviolet radiation of the sun: the face, ears, hands, scalp, shoulders, neck, or lips. In the case of forming on the lips, actinic keratoses are referred to as actinic cheilitis. AKs are the most common form of skin precancer, with around 58 million people in the United States having one or more spots of actinic keratosis (“Actinic Keratosis: Risk”). Because AKs are precancerous, if left untreated, they can result in a form of skin cancer known as squamous cell carcinoma, where squamous cells in the epidermis overproduce, and they are a risk factor for basal cell carcinoma (Oakley). These types of skin cancer will be described in further detail later in the paper. Initially, only 5-10% of AKs turn into skin cancer, but for patients with ten or more actinic keratoses, the risk increases to 10-15% (Coulson). AKs that are tender, thickening/enlarging, or ulcerated are often signs that squamous cell carcinoma is manifesting.

An actinic keratosis grows slowly and often manifests in people above the age of forty, yet this does not mean it will affect younger individuals. Actinic keratoses are typically 2.5 centimeters in diameter and are raised patches (Mcintyre et al.). Symptoms include dry and scaly skin that may be the same color as the skin but may also be more easily recognizable with colors ranging from pink to brown to red. In some cases, they can be hard and wart-like, forming a thin crust (Coulson). An actinic keratosis may burn or itch as it can become extremely dry. Actinic keratoses often appear on areas of the body most exposed to sunlight, as seen with the previous dermatological conditions. Similar to sunburn or signs of photoaging, actinic keratoses grow on the face, arms, hands, legs, neck, and scalp. Another symptom of actinic keratoses is an extremely dry lip, known as actinic cheilitis (Coulson). The scaly lip will never heal or may heal only to return. Scaly, white patches might appear, signaling the growth of a precancerous condition. Discoloration is also a common symptom of actinic cheilitis, with the lips often losing color and turning the same pigment as the skin. A less common symptom of actinic keratoses is when cutaneous horns form on the face; these horns are rare tumors that are often conical and formed of dead keratin, the structural protein found in the epidermis (Nair et al.). When an actinic keratosis develops in this form, it indicates that the patient has a higher chance of developing skin cancer, particularly squamous cell carcinoma.

An actinic keratosis may be treated using cryotherapy, typically freezing the skin with liquid nitrogen for patients who have AKs that are spread out or limited in number. The affected skin begins blistering and peeling, allowing the damaged skin to shed off for new skin (“Actinic Keratosis: Risk”). However, side effects include blisters, scarring, and permanent hyperpigmentation, where the skin is discolored (“Actinic Keratosis - Diagnosis”). Still, cryotherapy is generally highly effective and well-tolerated, with the procedure not requiring any local anesthesia. Another treatment option for actinic keratoses involves the use of a curette to scrape off the damaged skin. This process, known as curettage, mechanically excises abnormal cells and is used for treating a limited number of AKs that are typically thick (Mcintyre et al.). Electrosurgery is frequently used after curettage to destroy further abnormal skin layers and bring the skin to hemostasis, where it can stop bleeding from the scraped skin. In this procedure, a thin instrument is used to cut and eliminate the affected skin using an electric current, meaning therefore, local anesthesia must be used (“Actinic Keratosis - Diagnosis”). Side effects of curettage and the subsequent electrosurgery include infection, scarring, and discoloration. A further treatment option includes photodynamic therapy, where a photosensitizing agent — such as aminolevulinic acid or methyl aminolevulinate — is applied to the skin and then exposed to blue or red fluorescent light (Mcintyre et al.). An incubation period will be held until the cells die off, allowing for new and healthier skin to grow. However, photodynamic therapy can result in inflamed skin, swelling (edema), hyperpigmentation, scaling, redness (erythema), or a burning sensation. Medicated creams are available to treat AKs, such as topical fluorouracil, which is available in Efudex, Fluoroplex, and Carac. Fluorouracil works by blocking a methylation reaction to damage DNA/RNA creation, stopping the growth of atypical cells (Costa et al.). Side effects include irritation, seen as dryness, erythema, pain, or edema. Another topical treatment is

imiquimod, which is applied once a day and two or three times a week for sixteen weeks to treat AKs (Costa et al.). Imiquimod modifies immune responses, leading to apoptosis, or the death of abnormal cells. These topical creams typically have the same local side effects but may also present with fatigue, flu-like symptoms, and swelling under the skin (angioedema) (Mcintyre et al.). Finally, the anti-inflammatory drug diclofenac hinders the production of cyclooxygenase, making it difficult for the body's immune system to be suppressed, thus allowing for the reduction of tumors and AKs. Diclofenac must be applied twice daily for ninety days and may cause inflammation, scaling, or a burning sensation for a couple of weeks (Costa et al.).

Actinic keratoses are the most common premalignant lesions, meaning they are likely to form skin cancers. An actinic keratosis left untreated can result in squamous cell carcinoma; when squamous cells, found in the middle and outer layers of skin, begin to grow abnormally, resulting in AKs, they can result in tumors and cancer if not checked out (Coulson). Untreated squamous cell carcinomas can become invasive and spread to the rest of the body, including the lymph nodes, where white blood cells are held. Therefore, the growth of cancer and actinic keratoses can lead to serious complications; because of this, it is best for AKs to be treated as quickly as possible to completely eradicate the risk of developing skin cancer.

4.4. The role of ultraviolet radiation in the development of these conditions

The human skin has many protections that help shield against UV exposure. Immune cells, such as Langerhans cells and T lymphocytes, are found within the skin, as well as melanocytes, which form melanin. Melanin absorbs ultraviolet radiation, blocking the penetration of UV rays into the layers of the epidermis. Initial DNA damage can also be repaired with nucleotide and base removal mechanisms, as well as cell cycle checkpoints after DNA synthesis (Gromkowska-Kępa et al.). Even so, UV radiation can cause dermatological conditions and increase skin cancer risk. When UVB rays penetrate the dermis layer of the skin, sunburn, hyperpigmentation, and photoaging can be induced. This is due to the formation of reactive oxygen species (ROS), which can damage the cell's membranes, proteins, and DNA (Gromkowska-Kępa et al.). Oftentimes, ROS will injure the formation of collagen — the protein that is responsible for the skin's elasticity — thus causing premature aging in the form of sagging skin. UVA radiation also reaches the keratinocytes in the epidermis, changing the cells' polyunsaturated fatty acids and metabolism. The formation of these metabolites may result in inflammation of the skin, as well as skin pigmentation, which is another common dermatological condition. One of the most harmful effects of UV radiation occurs in the increase of matrix metalloproteinases (MMPs), which are responsible for tissue remodeling. However, MMPs cause the degradation of proteins such as collagen, elastin, matrix glycoproteins, and proteoglycan (Pittayapruek et al.). The enormous decay of these proteins contributes to the photoaging of the skin in the sense that it leads to wrinkles and sagging. Consequently, skin exposure will harm the skin, resulting in photoaging and sunburn.

5. SKIN CANCER: TYPES

5.1. Basal cell carcinoma

Basal cell carcinoma is the most common form of skin cancer, with around 3.6 million Americans being diagnosed with this type of skin cancer every year (“Basal Cell Carcinoma”). Moreover, basal cell carcinoma (BCC) makes up approximately 75% of nonmelanoma skin cancers, usually appearing in adults over the age of fifty (Nakayama et al.). Even so, basal cell carcinoma (BCC) is mostly curable and causes minimal damage when caught early. It occurs when one of the skin’s basal cells develops a mutation in its DNA due to UV radiation, thus promoting abnormal growth. These round basal cells are found at the bottom of the epidermis, and they produce new skin cells, pushing the old cells toward the skin’s surface, where they will fall off (“Basal Cell Carcinoma - Symptoms”). BCC often appears as a slightly translucent bump on highly exposed skin, such as the head and neck; in less common cases, basal cell carcinoma symptoms may develop in other areas of the body, including the genitals, forming skin lesions that will not heal. On fair skin, the lesion will be skin-colored or pink, while on darker skin, the bump may appear brown/black with a rolled border. These shiny bumps may bleed and scab over, and in some instances, tiny blood vessels can be visible (“Basal Cell Carcinoma - Symptoms”). Skin lesions can also take the form of scaly patches or waxy scar-like growths without a defined border. If not caught early, these lesions can spread deeply into the skin and wrap around nerves and blood vessels, invading muscles and bones; in some cases, basal cell carcinoma can cause disfiguring growths, drastically changing the way the patient appears. BCC growth is quite slow and often takes months to years to evolve and continue to grow.

There are over twenty histological growth patterns of BCC. This paper will delve into the most common and recognizable types. Nodular BCC is composed of islands of malignant cells with peripheral palisading, meaning they form parallel arrays around the tumor in the dermis. It is the most common type of facial basal cell carcinoma, forming shiny nodules that may have central ulcerations, causing the edges to appear rolled (McDaniel and Steele). Superficial BCC is the most common growth pattern of basal cell carcinoma in younger adults, frequently forming on the shoulders. It appears as scaly and irregular plaques with thin, translucent rolled borders. Superficial BCC has basaloid cells that arise from the basal (bottom) layer of the epidermis and usually stay within the dermis. Furthermore, morphoeic, or sclerosing, basal cell carcinoma is found in the mid-facial sites, creating a scar-like plaque that is waxy in appearance and has unclear borders. It occurs with thin strands of basaloid cells that invade the dermis and are surrounded by fibrous stroma. Morphoeic BCC can infiltrate cutaneous nerves and invade deeply, thus becoming more dangerous (McDaniel and Steele). Finally, basosquamous carcinoma has an infiltrative growth pattern and is more aggressive than other forms of BCC. It features large, pale cells without peripheral arrangement and shows features of both basal and squamous cell carcinomas (McDaniel and Steele). However, the clinical and histological features are more closely related to BCC.

Treatment for BCC depends on the type, location, and size, as well as whether the cancer is recurring or not. Basal cell carcinoma is usually treated with surgery that can remove the cancer and healthy tissue around it to prevent any spread. Excisional surgery is one example that is used

to treat small and early BCCs that have not spread and are not likely to come back, such as on the chest, back, hands, or feet (“Basal Cell Carcinoma - Diagnosis”). During this procedure, the surgeon removes the entire tumor, as well as the surrounding tissue, using a scalpel. The surrounding margin of healthy skin is then examined to ensure the cancer has not spread beyond the margin (“Basal Cell Carcinoma - Diagnosis”). Mohs surgery is another treatment option where the surgeon removes the cancer layer by layer until no abnormal cells are present. By doing so, the surgeon can make certain that the entire growth is removed without having to remove excess healthy tissue. Mohs surgery is used for aggressive BCCs that have a higher chance of recurring (McDaniel and Steele). It minimally harms tissue and has the highest possible cure rate: 99% of tumors are treated for the first time with Mohs surgery (Dim-Jamora and Perone). Other treatments include curettage and electrodesiccation, which remove the surface of the cancer with a curette and then sear the base of the cancer with an electric needle to destroy the remaining cancer cells. Radiation therapy, cryosurgery, laser surgery, photodynamic therapy, and topical treatments may also be used when surgery is not an option.

5.2. Squamous cell carcinoma

Squamous cell carcinoma (SCC) is the second most common form of skin cancer, with around 1.8 million cases diagnosed in the United States each year (“Squamous Cell Carcinoma Overview”). There are two types of squamous cell carcinoma: cutaneous, meaning it pertains to the skin, and metastatic, which is cancer that arises in other parts of the body, such as the lungs, mouth, or throat. For the purposes of this paper, only cutaneous SCCs will be discussed. Squamous cell carcinoma is the cancer of squamous cells, which are flat cells near the top layer of the skin in the epidermis; squamous cells are continuously shed off as new skin cells form, and they are found on top of the aforementioned basal cells. When SCC is caught early, it is most likely curable, with cutaneous squamous cell carcinoma not being life-threatening (“Squamous Cell Carcinoma of the Skin - Symptoms”). However, if allowed to develop, SCCs can grow large and spread to other parts of the body that are more dangerous, causing serious implications. Symptoms of squamous cell carcinoma include a rough, firm bump, known as a nodule. The bump may be pink, red, black, or brown and is likely to occur in sun-exposed regions of the skin. Other signs of squamous cell carcinoma are thickened wart-like skin, growths with depressions in the centers, sores with scaly crusts, scaly and red patches, or wounds/sores that do not heal or constantly reappear (“Squamous Cell Carcinoma of the Skin - Symptoms”). The presence of actinic keratoses on the skin is another common form of SCC development.

Squamous cell carcinoma is caused by excessive UV radiation, tanning beds, or lamps. The use of these carcinogens can damage and mutate p53 proteins, which act as a tumor suppressor by regulating cell division to stop the abnormal growth of cells. However, these carcinogens mutate the p53 protein, causing it to be defunct and thereby allowing for the relocation of DNA-damaged squamous cells (Hadlan et al.).

Treatment for squamous cell carcinomas depends on where the cancer is, how large it is, the preference of the patient, and how fast the cancer is spreading. If the cancer is small and has a

low risk of spreading, surgery is very similar to the treatment used for basal cell carcinomas. These surgeries include curettage and electrodesiccation, laser therapy, cryosurgery, and photodynamic therapy. For larger skin cancers, treatments include excisional surgery, Mohs surgery, and radiation therapy (Ludmann). However, because SCCs are more likely to become metastatic than BCCs, there are a variety of treatments for squamous cell carcinoma when it spreads to other parts of the body. Chemotherapy, which uses strong medicines to kill cancer cells and other fast-growing cells in the body, can be used. However, chemotherapy also targets hair cells and cells in the gastrointestinal (GI) tract, causing side effects of hair loss and nausea (Ludmann). Targeted therapy may also be used where medicines attack specific chemicals in cancer cells, thus blocking these chemicals and causing the cancer cells to die. Targeted therapy is generally used alongside chemotherapy. Another option for treatment includes immunotherapy, which is when medicine is given to help the immune system fight cancerous cells (Squamous Cell Carcinoma of the Skin - Diagnosis"). FDA-approved immunotherapy medications include cemiplimab-rwlc and pembrolizumab, which are both given through IV infusion. Because cancer cells survive by hiding from the immune system, these medications help the immune system locate and kill cancerous squamous cells (Ludmann). Immunotherapy should be considered when other treatments are not an option and the cancer is too advanced.

5.3. Melanoma

Melanoma is the least common form of skin cancer, but it is viewed as the most dangerous since it has a higher likelihood of spreading to other parts of the body. It begins in the melanocytes, which are the cells that make the pigment melanin, giving skin its color; melanin also protects the dermis and deeper layers of the skin from sun damage ("What is Melanoma"). Melanoma begins on parts of the skin most exposed to the sun, and will rarely develop in areas such as the nose or throat; even so, melanoma can sometimes form in the eye or areas such as the genitals. There are multiple types of melanoma, such as superficial spreading melanoma (which makes up 70% of melanomas of the skin) and nodular melanoma (which accounts for 20% of skin melanomas) ("What is Melanoma"). Superficial melanomas tend to start in existing moles, or they may be seen as a dark spot on the skin that changes shape, growing bigger. Around 20-30% of melanomas are found in existing moles, while 70-80% appear on normal skin ("Melanoma"). On the other hand, nodular melanoma tumors appear as nodules, or raised bumps, on the skin, and they tend to grow in deeper layers of the skin. Lentigo maligna melanoma is another type that occurs in older people, starting as an abnormally shaped colored spot that grows slowly ("What is Melanoma"). Moreover, in rare cases, acral-lentiginous melanoma can occur, where the tumor develops under a nail, the soles of the feet, or the palms of the hands. Acral-lentiginous melanoma is more common in people with darker skin. Melanoma that develops in the mucous membrane — the tissue that lines the nose, mouth, esophagus, anus, urinary tract, and vagina — is known as mucosal melanoma ("Melanoma - Symptoms"). Finally, ocular melanoma is when melanoma occurs in the eye, or more specifically in the uvea — the layer of tissue beneath the sclera (white outer layer of the eyeball) and cornea.

Because melanoma can spread, finding the tumor at an early stage is crucial, as survival rates will drop if the cancer reaches the lymph nodes and distant organs. Warning signs of melanoma can be remembered with mnemonic devices of the ABCDEs (Figure 3). A is for asymmetry, meaning the lesion is asymmetrical and thus looks different from a typical mole (“What to”). B is for the border, as melanoma borders are uneven, with scalloped edges. Additionally, C is for color, with a warning sign being that melanomas typically have multiple shades. Benign moles are usually a single shade of brown, while melanomas can contain multiple shades of brown, tan, black, red, white, or blue (“Melanoma”). D is for diameter, with a mole that changes in size usually being a common sign of skin cancer. A mole that is larger than $\frac{1}{4}$ in (6mm) should be checked out by a dermatologist (“Melanoma - Symptoms”). Finally, E represents the sign of evolving, with any change in size, shape, color, or elevation, or the symptom of bleeding, itching, or crusting being a warning sign of melanoma (“What to”).

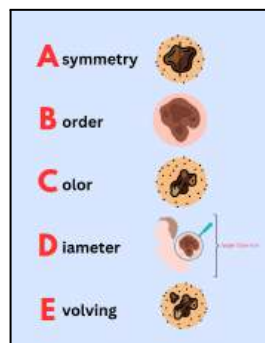


Fig 3: the ABCDE warning signs of melanoma

Melanoma is divided into stages, which are used to determine which treatment is best. The stages are determined based on tumor thickness, ulceration (the formation of the skin over the melanoma), spread to the lymph nodes, and metastasis to distant parts of the body (“Stages”). Stage 0 — also known as melanoma in situ — is when abnormal melanocytes are found in the epidermis, but there are no signs that they have spread to other parts of the body. In stage 1, cancer has formed, and the main tumor is less than 2mm; however, there is still no sign that the cancer has spread. Stage 1 is divided into stage IA, where the tumor is less than 1mm thick, whereas in stage IB, the tumor is more than 1mm and without ulceration (“Melanoma Treatment”). Stage II is when the main tumor may be thicker than 4mm without ulceration, and there are no signs that the cancer has spread (“Stages”). Stage II is divided into stages IIA, IIB, and IIC, depending on the thickness and whether any ulceration was present. In stage III, the main tumor can be any thickness, and it may or may not have ulcerated. Stage III melanoma has spread to the lymph nodes and/or nearby skin to form satellite tumors (“Melanoma Treatment”). It may have also spread to the skin lymphatic channels around the tumor; nevertheless, there are still no signs that the cancer has spread to distant parts of the body. Subgroups depend on the thickness, ulceration, and where the cancer has spread (“Stages”). Finally, stage IV is when the main tumor can be any thickness, it might be ulceration, and it might have spread to nearby lymph nodes. The

cancer has spread to other parts of the body, such as the liver, lung, spinal cord, soft tissue, bone, GI tract, or brain (“Melanoma Treatment”).

Surgery is the primary form of treatment for all stages of melanoma, where a local excision is used to remove the cancer as well as normal tissue around it (“Melanoma Treatment”). If the cancer has spread to the lymph nodes, surgery might be used to remove the lymph nodes. If the melanomas are small and thin, surgery may be the only form of treatment needed; however, for melanomas that cannot be removed completely with surgery, radiation therapy can be used (“Melanoma - Diagnosis”). Radiation therapy uses high-energy X-rays, protons, or other sources of radiation to kill the cancer cells and keep them from growing. If the melanoma has spread to the lymph nodes, radiation therapy can be directed there (“Melanoma - Diagnosis”). Moreover, radiation therapy can also relieve symptoms of melanomas that have spread to other areas of the body. Immunotherapy is another viable option where medicine is used to help the body’s immune system fight the cancer cells (“Melanoma Treatment”). If the melanoma doesn’t respond to other treatments, chemotherapy can be used, where drugs stop the growth of cancer cells by killing them or stopping them from dividing. Chemotherapy can be given in a vein in the patient’s arm or leg during an isolated limb perfusion (“Melanoma - Diagnosis”). During this procedure, the blood to and from the limb is stopped to keep the chemotherapy medicines near the melanoma and to prevent them from affecting other parts of the body. Other forms of treatment include targeted therapy — where drugs or other substances are used to identify and attack specific cancer cells. In signal transduction inhibitor therapy, signal transduction inhibitors block signals that pass from molecules, thus killing cancer cells. Oncolytic virus therapy is another form of targeted therapy where a virus is used to infect and break down cancer cells without affecting other cells (“Melanoma Treatment”). Finally, angiogenesis inhibitors are a type of targeted therapy that blocks the growth of new blood vessels, thereby preventing the growth of tumors (“Angiogenesis”).

6. SKIN CANCER: RISK FACTORS

6.1. Family history

A family history of skin cancer often increases the risk of getting skin cancer. For example, in the case of melanoma, around 10% of all patients diagnosed with melanoma have a family member with a history of the cancer (“Melanoma”). Therefore, when melanoma is diagnosed, it is often recommended that close relatives also be examined. In further depth, several genes are associated with the different forms of skin cancer. Basal cell nevus syndrome is a hereditary syndrome caused by pathogenic variations in the PTCH1 and PTCH2 genes. BCNS is typically associated with a higher risk of basal cell carcinoma. Similarly, hereditary syndromes such as oculocutaneous albinism, epidermolysis bullosa, and Fanconi anemia often lead to an increased risk of squamous cell carcinoma (“Genetics”). Finally, the alterations in genes most associated with a higher melanoma risk are CDKN2A (cyclin-dependent kinase inhibitor 2A) and BAP1 (BRCA1-associated protein-1). CDKN2A is a germline tumor suppressor gene, meaning it

regulates cell growth. Consequently, when it mutates, uncontrolled cell growth can occur, contributing to melanoma. CDKN2A is also unusual because it affects two separate proteins that have different functions: p16, which regulates the cell cycle, and p14ARF, which also regulates the cell cycle and apoptosis. Pathogenic variants in CDKN2A account for 35-40% of all familial melanomas (“Genetics”). Another tumor suppressor gene that increases the risk of melanoma is MC1R (melanocortin 1 receptor). Furthermore, BRCA2, a hereditary breast cancer gene, is also associated with a slightly increased risk of melanoma. If a patient is suspected of having melanoma genes, their family can be screened to identify those with defective genes. Finally, an autosomal recessive disease known as xeroderma pigmentosum (XP) can increase the risk of all skin cancers. XP is rare, and it is characterized by extreme sensitivity to UV radiation as well as mutations in nucleotide excision repair (Lehmann et al.).

6.2. Fair skin

People with fairer skin typically have an increased risk of skin cancer because they have less melanin, which is a UV-protective pigment. According to Thomas Fitzpatrick and the Fitzpatrick skin typing classification, there are six main types of skin that affect the skin’s reaction to sun exposure. Skin type I involves those with very light skin that often has freckles and does not tan. Those with skin type I tend to have reddish hair and blue or gray eyes, and UV radiation will lead to sunburn within ten minutes due to the lack of melanin. Essentially, the skin will always burn and never tan (“What Increases”). Skin type II also involves light skin with freckles, yet these individuals have blond/brown hair as well as all eye colors. With skin type II, UV radiation leads to sunburn within twenty minutes, and the skin burns easily and tans poorly. Skin type III involves those with light or light brown skin who rarely have freckles. Hair and eye color are usually dark brown. Contrary to the other two skin types, with skin type III, the skin tans easily, and sunburns only occur occasionally and are mild (Gupta and Sharma). Moreover, skin type IV describes people with light brown or olive-colored skin and no freckles. These individuals typically have dark brown hair and brown/dark brown eyes. UV radiation leads to sunburn within fifty minutes, and the skin burns minimally yet tans easily (“What Increases”). Skin type V involves those with dark brown skin, dark brown/black hair, and dark brown eyes. UV radiation will only lead to sunburn after more than sixty minutes, and the skin will tan darkly more easily. Furthermore, the skin rarely burns with skin type V. Finally, the last skin type, skin type VI, refers to dark brown/black skin as well as black hair and dark brown eyes (“What Increases”). UV radiation will only lead to sunburn after more than sixty minutes, and the skin rarely burns and will not tan darkly. Skin types I and II involve those who live or descend from Scandinavia or Great Britain, while those in type IV mainly live in the Mediterranean or similar regions. Types V and VI refer to those typically from areas with darker skin, such as certain areas of Asia and Africa (“What Increases”). While those with darker skin are less likely to get skin cancer, they are still at risk for developing acral lentiginous melanoma, which occurs on the soles of feet, palms of hands, and beds of nails (“Risks”).

6.3. Atypical moles

Atypical moles, known as dysplastic nevi, are a risk factor for skin cancer; it is important to differentiate that having atypical moles does not mean that skin cancer is present but that a risk factor is present. Dysplastic nevi differ from regular moles since they are typically larger (greater than 5mm), and their color or border is unusual (“Common”). For instance, they can range from pink to dark brown and may have a border that fades into the skin around the mole or is ragged, giving the mole an irregular (not round) shape. The texture of the mole will also be atypical, with most dysplastic nevi being flat with a smooth, scaly, or pebbly-like surface that is raised (“Common”). Atypical moles can be found anywhere on the body but are usually frequent in areas that witness a lot of sun, such as the torso, extremities, head, neck, scalp, or even calves (although primarily for women). The identification of a dysplastic nevus can be done using the ABCDE (asymmetry, border, color, diameter, evolution) guidelines, which are described in more detail in the previous section (Wensley and Zito). There are five subtypes of dysplastic nevi: fried-egg subtype, where the mole has a raised central portion with a dark brown color; lentiginous subtype, where the mole is flat with a brown or dark brown color; seborrheic keratosis-like subtype, meaning the dysplastic nevus is rough and dark brown; targeted subtype, where the mole has varied pigmentation; and the erythematous subtype in which the mole has a pink pigmentation (Wensley and Zito). The amount of dysplastic nevi varies depending on the person, with people who have more atypical moles typically having more common moles. However, the risk factor of dysplastic nevi increases in proportion to their number; having ten or more atypical moles can increase the risk of melanoma by twelve times (“Atypical”). However, only rarely does a dysplastic nevus turn into melanoma. The best way to be safe with dysplastic nevi is for the patient to keep track of all their moles and visit their dermatologist if there is anything new, changing, or unusual (“Common”). This can ensure that if cancer occurs, it will be found and treated as efficiently as possible.

6.4. Gender

A possible explanation for why men are more likely to get skin cancer is due to biological factors. To begin with, men and women have different characteristics in their skin; a man’s skin is thicker and has less fat beneath, and it also contains more elastin and collagen, contributing to the skin’s firmness. These differences make men’s skin react more intensely to UV rays, therefore making the skin more likely to be damaged, according to multiple studies (“Why”). Other studies have found that women’s skin can heal any sun damage more efficiently than men’s skin (“Why”). Other biological components include the presence of estrogen and testosterone; estrogen has been found to potentially cause an increased antibody and inflammatory response against melanomas, while testosterone reduces the immune response (Schwartz et al.). This is because estrogen receptor beta (ER-β) is negatively associated with melanoma invasiveness and tumor thickness (Schwartz et al.), and its expression decreases in melanoma progression, reinforcing its role as a tumor suppressor (Marzagalli et al.). Furthermore, people with higher estrogen levels tend to respond better to treatment, having a higher chance of survival (“Why”).

Genetic differences may also play a role in the prevalence of skin cancer among men. The X chromosome has 1500 oncogenes and tumor suppressor genes, while the Y chromosome only has 344, and the regulation of these genes is critical to stop cancer (Schwartz et al.). Differences in autosomal genetic variations may also cause men to be more susceptible to skin cancer. For example, a non-synonymous single nucleotide polymorphism (SNP), rs16891982, in the SLC45A2 gene results in a higher risk of melanoma in males. SNPs relating to pigmentation may also be a potential genetic cause for males being more likely to get melanoma, with SNPs in some genes shown to increase melanoma in males compared to females (Schwartz et al.).

7. SKIN CANCER: PREVENTATIVE MEASURES

7.1. Sunscreen use

One of the best ways to prevent skin cancer is to use sunscreen on an everyday basis. The sunscreen used should be broad-spectrum, meaning it combats both UVA and UVB rays, and it should have an SPF of at least thirty (“How to”). Sun Protection Factor correlates to how well the sunscreen will protect an individual’s skin from UV rays; an SPF of 15 relates to 93.3% of UVB absorption, an SPF of 30 correlates with 96.7%, an SPF of 45 corresponds with 97.8%, and an SPF of 50 correlates with 98% UVB absorption (Wilson et al.). For an adult body, one ounce (or around two tablespoons) should be applied to the entire body thirty minutes before going outside and reapplied after two hours (“How to”). It is important to note that sunscreen is still needed under clothes (depending on the fabric) and on cloudy days. Additionally, sunscreen should be applied to areas such as the tops of one’s feet, the neck, the ears, the nose, and the scalp as these areas are at risk for sunburn and commonly missed (“How to”).

The ingredients in sunscreen can impact what UV rays the sunscreen is protecting against. To exemplify, ingredients such as padimate O, octinoxate, octisalate, octocrylene, and ensulizole are commonly used to protect against UVB rays, while ingredients including oxybenzone, meradimate, avobenzone, and terephthalylidene dicamphor sulfonic acid protect against UVA rays (Wilson et al.). The type of sunscreen can also impact how effective they are and how regularly it needs to be applied. Mineral, or physical, sunscreens work by reflecting or scattering UV rays, using ingredients such as titanium dioxide and zinc. These physical blockers create a barrier on the skin to reflect any UV light, thus protecting the skin (Adams). On the other hand, chemical sunscreens are more popular since they are thinner and protect the skin by changing the chemical structure of UV rays to reduce sun damage. They work by absorbing high-intensity UV rays, exciting them to a higher energy state, and returning them to the ground state, therefore converting the absorbed energy into a longer and lower energy wavelength that is less harmful (Wilson et al.). However, chemical sunscreens are less effective than mineral sunscreens and will need to be reapplied more frequently.

7.2. Protective clothing

Protective gear is one of the easiest and most effective ways to protect against the risk of sun damage. Protective clothing, such as long-sleeved shirts and pants, can provide a physical

barrier against UV rays; even better, this barrier will not wash or wear off, as is the case with sunscreen (“How to”). Clothing that is effective against UV rays will have a UV protection factor (UPF), a measure that relates to the amount of UV radiation that can penetrate fabric and reach the skin. A UPF of 50+ offers high protection, with a UPF of 50 allowing only 2% of UV rays to reach the skin (“Sun Protective,” *The Skin Cancer Foundation*). In addition, the effectiveness of clothing depends on a variety of factors. Dark or bright colored fabrics will absorb UV rays, offering better protection (“Sun Protective,” *The Skin Cancer Foundation*). The material of clothing also plays a role, with synthetic/semi-synthetic fibers like polyester offering more protection than loose linen; finally, the fit of the required clothing can be a factor, with tightly-woven textiles permitting less direct skin exposure (Lu and Ilyas). Another protective measure for skin cancer includes hats. Skin cancers like basal cell carcinoma and squamous cell carcinoma often appear on the head and neck, so wearing a hat can drastically reduce this risk (“Sun Protective,” *The Skin Cancer Foundation*). It is generally recommended to wear a wide-brim hat that is at least three inches wide to protect these areas as well as other overlooked places, such as the scalp, shoulders, upper back, and tips of the ears (“Sun Protective,” *Skin Cancer Institute*). Hats should have UPF-rated materials or a thick material, and it is important to choose a tight-knit hat rather than a loosely woven straw hat, as these will further block the risk of UV rays (“Sun Protective,” *Skin Cancer Institute*). Finally, the last most effective sun protective measure includes sunglasses with both UVA and UVB filtering and large frames. Ideally, the lens should have 99-100% UVA/UVB protection to ensure their utmost effectiveness (“Sun Protective,” *Skin Cancer Institute*). Ultimately, the most significant rule with protective gear is to cover up the skin as much as possible. With clothing, opt for outfits that cover more skin, like a swim shirt instead of a bikini. Similarly, a wide-brimmed hat will be much more effective than a cap, and large-framed sunglasses will also offer more protection than small-framed ones. While these options might be less trendy, in the end, they are one of the best ways to protect the skin from UV rays and lower the risk of skin cancer (Figure 4).



Fig 4: Sun protection strategies with clothing

8. PUBLIC HEALTH IMPLICATIONS AND AWARENESS

8.1. Lack of public awareness regarding sun exposure

Many Americans are unaware of how to protect themselves from the sun; according to a 2022 survey consisting of over 1,000 adults by the American Academy of Dermatology

Association, 43% of respondents did not know that shade protects a person from UV rays (“New”). Minority and immigrant populations in the United States also lack critical information regarding sun exposure and skin cancer. A study found that out of the 206 immigrants/minorities surveyed, 25.4% did not know about skin cancer, 20.7% believed that those with darker skin could not get skin cancer, and 58.2% never or rarely conducted self-skin checks (Jacobsen et al.). With the lack of awareness about skin cancer comes a higher risk of getting skin cancer. Most deaths caused by cutaneous melanoma come from patient delay, which is largely attributed to a lack of knowledge about skin cancer (Rhodes). For example, many patients delay getting a mole assessed by a physician due to a lack of knowledge; in a survey of 1,245 people in the UK, 42% of people said that they would probably not see a physician for a new mole, while 22% said they would definitely not (Rhodes). Hence, ignorance surrounding skin cancer and its signs can lead to negative consequences, suggesting the need for public awareness initiatives that can help create more informed and healthy citizens.

8.2. Importance of public awareness

Public awareness regarding skin health and the risks of sun exposure is crucial in order to prevent skin-related health issues and promote overall well-being. To begin with, increasing awareness will undoubtedly lead to the prevention of skin cancers, as more individuals learn the importance of protecting the skin and adopting preventative behaviors such as using sunscreen, wearing protective clothing, and seeking shade. In a study analyzing the effectiveness of knowledge-based interventions, prior to intervention, only 14% of the study population believed that people with dark brown skin could get sunburn, compared to 62% of the same group after the intervention (Kailas et al.). This clearly demonstrates how public awareness is needed to help people learn methods to keep their skin safe and make better decisions promoting skin health. More knowledge about the effects of UV rays will undoubtedly prompt reduced incidences of sunburns, which not only cause immediate pain and discomfort but also increase the risk of long-term skin damage and skin cancer. Finally, educating the public about skin health encourages the early detection of dermatological conditions. Awareness initiatives can promote regular skin checks and knowledge about what to look for, significantly improving the outcomes for those with skin concerns.

In the end, public awareness regarding the relationship between the sun and the skin will not only lead to healthier individuals but a healthier community. Awareness campaigns can create cultural change, where communities shift cultural norms regarding tanning and sun exposure. This can cause a greater acceptance of skin protection and a decrease in the societal pressure to achieve tan skin. Public awareness can also result in policy and environmental changes, such as sunscreen usage in schools, regulations on tanning salons, and the creation of public spaces that prioritize shade, all of which support community health. It is therefore abundantly clear that with the rise of public knowledge regarding the skin, the world will be a healthier place.

8.3. Successful public health campaigns and initiatives

Many health associations have promoted public health campaigns and initiatives promoting sun safety and ensuring a healthier society. One of these is Australia's "Slip, Slop, Slap" campaign, which was launched in the 1980s and popularly told people to slip on a shirt, slop on sunscreen, and slap on a hat. The slogan was later updated to "Slip, Slop, Slap, Seek, Slide" in 2007 to include the significance of seeking shade and sliding on sunglasses ("Slip, Slop, Slap, Seek, Slide"). This initiative is largely credited with shifting the attitude toward sun protection and reducing the instances of skin cancer. In fact, the rate of melanoma cases fell from 25 per 100,000 in 1996 to 14 per 100,000 in 2010 among people aged 20 to 24 ("Slip, Slop, Slap, Success"). Finally, the SunSmart program based in Australia has also played a large role in the sun safety public awareness campaign. Managed by Cancer Council Victoria and the Victorian government, this program promotes sun safety through education, community involvement, and policy advocacy ("About"). It also includes resources such as the SunSmart Global UV app, which lets users know when UV levels are damaging. However, one of SunSmart's most effective campaigns was the "UV. It all adds up" campaign in 2015, demonstrating that everyday outdoor activities can result in skin cancer risk ("About"). Overall, all of SunSmart's programs and initiatives have proven effective as melanoma rates have declined or stabilized in all age groups under sixty in Victoria ("About"). While these public health initiatives have proven effective within Australia, America falls short in its public health initiatives regarding skin cancer. Despite skin cancer (melanoma) being the 17th most common cancer worldwide in America (Wang et al.), it proves to be the most common form of cancer, with current estimation being that one in five (20%) Americans will develop skin cancer in their lifetime ("Skin Cancer").

9. SUGGESTIONS FOR FUTURE RESEARCH

Despite the fact that awareness about skin cancer has reached an all-time high, with more and more people purchasing sun protection such as sunscreen, skin cancer rates are on the rise (Handel and Ramagopalan). The diagnosis of nonmelanoma skin cancer increased by 77% in the U.S. between 1994-2014, while from 2014 – 2024, the diagnosis of melanoma increased annually by 32% ("Skin Cancer Facts"). These findings illustrate a perplexing and concerning trend that is occurring, and they suggest that additional research is needed to investigate this trend. While hypotheses have been made, few if any conclusions have been reached to fully explain this pattern (Lapides et al.). Therefore, future research should be conducted to address these gaps in current knowledge.

For example, research should be conducted on sunscreen applications. While sunscreen efficacy is well-established in controlled laboratory settings, its effectiveness in real-world scenarios remains less certain. Research should investigate how individuals apply sunscreen, the frequency of reapplication, and whether common usage patterns lead to gaps in protection. After all, despite more people buying sunscreen, they are using it incorrectly and not to their best advantage. Only 13% of Americans use sunscreen on their body regularly, and the majority of people (58%) only wear sunscreen during the summer months; moreover, 39% of Americans only apply their sunscreen once, even though it needs to be reapplied every two hours ("Sun Safety

in”). Consequently, additional studies should be conducted to track populations over extended periods, monitoring their sunscreen habits and comparing them to skin cancer incidence in order to identify potential gaps where further knowledge about sun-protective measures could be useful. In addition, further research must be conducted on the behaviors of individuals; for example, individuals who use sunscreen inadvertently extend their time in the sun by 13–39% longer, believing they are fully protected, thereby leading to greater UV exposure (Autier). Hence, research exploring the psychological aspects of sunscreen use, including risk compensation behaviors, is needed to ensure safer practices while being exposed to the sun. It could help refine public health initiatives to emphasize sun protection strategies that go beyond sunscreen alone, ensuring safer behaviors.

Ultimately, the most important aspect that can be researched further is the effectiveness of current public health campaigns. Future research should focus on evaluating skin cancer initiatives to assess their impact and identify the elements that contribute to their success or drawbacks. Research should also focus on finding the best ways to encourage sun protection in different groups of people, especially young adults and teenagers. This could demonstrate how, perhaps, some campaigns may be more effective with a certain age group than others, allowing programs to be more personalized and thus more effective. This would not only enhance awareness of the risks but also empower individuals to make informed decisions about sun exposure.

10. CONCLUSION

In conclusion, this research paper has explored the multifaceted effects of sun exposure on dermatological conditions and the increased risk of skin cancer. UV radiation directly correlates with the development of various skin disorders, such as sunburn, photoaging, and actinic keratosis. UV exposure may also result in the development of various skin cancers, which can be deadly. There is a heightened vulnerability to skin cancer associated with specific risk factors such as fair skin, age, and family history. Hence, individuals with prior risk factors should be additionally cautious and meet with specialists if changes in the skin are noticed. This paper also provides an evaluation of public health campaigns, underscoring the critical role of education and prevention strategies in reducing skin cancer rates. Understanding the intricate relationship between sun exposure, skin health, and cancer risk is essential for effective prevention and early detection strategies. This knowledge not only informs public health initiatives but also empowers individuals to make informed choices regarding their sun protection habits. Moreover, prioritizing sun protection and maintaining skin health should be a universal concern. To navigate the balance between enjoying outdoor activities and safeguarding our skin, it is imperative to adopt preventive measures, promote awareness, and continue fostering a culture of skin health that can ultimately reduce the burden of skin cancer in our communities.

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How Do Delays to Individual Aircraft Affect Overall Runway Congestion and Delays at LAX? By Bob Zang

Abstract

Flight disruptions at big global airports frequently trigger chain reactions that worsen overcrowding and logistical bottlenecks. Using Los Angeles International airport (LAX) as a case, this research introduces a model to study how delays propagate through multiple days of LAX flight data. Drawing on 13 days of detailed June 2025 flight records obtained from Aviationstack, we derive a dataset featuring both planned and real times for incoming and outgoing flights. The modelling approach taken consists of two steps. Firstly, it employs regression analysis to measure the impact of elements and incoming delays on subsequent departure delays. Secondly, it applies those findings within a point process model that mimics how initial interruptions multiply within LAX's interdependent incoming and outgoing procedures. Findings indicate that small incoming delays-usually less than 10 minutes - can escalate total system holdups under high volume conditions, underscoring the need for proactive and time-sensitive interventions.

Introduction

Flight delays are a well-documented and persistent challenge for high-capacity international airports. (Ferguson et al. 311) Studies across air traffic management literature have shown that such delays cause inefficiencies in airport systems, extending beyond isolated schedule disruptions to cause ripple effects throughout the broader network. (Fleurquin et al., 330) These systemic inefficiencies have been estimated to cost billions annually in economic loss, passenger disruption, and increased fuel consumption.

At Los Angeles International Airport (LAX)—the fifth busiest airport in the world by passenger traffic as of 2023 — the potential for such disruptions is especially acute during peak hours. With four parallel runways, high arrival/departure throughput, and tightly sequenced turnaround operations, even minor disturbances can propagate across a day's flight schedule. At LAX, which maintains one of the world's most concentrated flight schedules, even a single late arrival can delay gate use, extend turnaround, and disrupt departure sequencing. Looking ahead, these vulnerabilities are expected to escalate as LAX prepares to accommodate intensified traffic loads during major international events, including the 2026 FIFA World Cup and the 2028 Summer Olympics. These events will likely push the airport to its operational limits, underscoring the urgent need for robust models that capture how localized delays spread through the airport system.

Operational flight data provide a valuable basis for modeling aircraft and airport behavior, offering insights that can guide strategies to reduce congestion and improve efficiency. (Ball et al. 10; AhmadBeygi et al. 347). In this paper, the challenge of predicting and understanding delay propagation at LAX is addressed through a two-stage modeling framework. First, a regression model is developed to estimate the airport-induced component of each flight's

departure delay, based on variables such as turnaround time, arrival punctuality, and departure hour. Secondly, these estimates are fed into a point process simulation that captures delay propagation dynamics across interacting arrival and departure flows at LAX. This combination of empirical prediction and stochastic simulation enables us to better understand delay propagation in congested airport environments, hopefully leading to better informed management decisions.

Literature Review

Delay propagation in air transportation systems has been extensively examined through both network science and operations research. Fleurquin et al. (2013) used data from the U.S. Bureau of Transportation Statistics to analyze how delays spread across the national airspace system. By representing airports and flights as a dynamic network, the authors demonstrated that delays cluster in time and space, producing a contagion-like process that can influence the entire system. This work highlighted the structural role of hub airports and aircraft rotation as primary channels for delay propagation. Building on this network perspective, Pyrgiotis et al. (2011) introduced the Approximate Network Delays (AND) model, which conceptualizes airports as stochastic queueing systems and simulates the transfer of delays between interconnected nodes. The model integrates queueing dynamics with scheduled demand profiles, showing that peak-hour disruptions at one location can significantly affect performance at connected hubs. Together, these studies underscore the inherently systemwide nature of delay propagation and highlight the importance of understanding localized bottlenecks within the broader network.

The literature has also advanced predictive models for estimating flight delays from operational variables. AhmadBeygi et al. (2008) developed a probabilistic framework that incorporates arrival delay, turnaround duration, and congestion levels to estimate departure delays, using regression analysis to distinguish between inherited and locally induced disruptions. Congestion levels are not included in the present regression model, which instead focuses on arrival delay, turnaround duration, and departure hour. Late arrivals and short turnarounds were identified as strong predictors of downstream delays—an insight directly relevant to the regression model in the present study. In a contrasting approach, Balakrishna et al. (2010) applied a neural network trained on surface movement data to predict taxi-out times at John F. Kennedy International Airport. Taxi-out time is the period from gate pushback to takeoff, while departure delay refers to the difference between the scheduled and actual pushback or takeoff. While effective in capturing nonlinear patterns, the limited interpretability reduced its operational adoption, illustrating the trade-off between complexity and transparency. Chatterji and Sridhar (2001) contributed further by applying analytical queueing models to air traffic flow management, showing that probabilistic congestion estimates can support air traffic flow adjustments, such as modifying routes or sequencing to reduce congestion. Although not explicitly designed for delay prediction, this work informs the point process simulation used in the second part of the methodology.

A smaller body of research addresses the operational characteristics of specific airports, including Los Angeles International Airport (LAX). FAA internal reviews and observational reports from 2020 to 2023 identify gate conflicts, tightly sequenced turnaround schedules, and recurrent departure queues as key sources of delay. Sandhu and Liang (2016) provided further insight through discrete-event simulations of departure wave congestion at LAX, documenting a “departure clumping” pattern during late afternoon push periods. The study demonstrated that small deviations in arrival times could trigger taxiway congestion, particularly when turnaround buffers were reduced. Although this work focused on surface-level interactions, it supports the decision in the present research to incorporate scheduling variables such as turnaround time and departure hour into the predictive modeling framework. In contrast, the present study moves beyond clustering analysis to develop a predictive framework embedded in a point process model.

An additional strand of the literature examines the temporal clustering of delays using point process models. Itoh and Mitici (2022) developed a queueing-based model for Tokyo International Airport that treated arrival delays as self-exciting events. Using radar track data and scheduled arrival information, the authors modeled the formation and spread of delay bursts and evaluated the potential benefits of interventions such as time-based flow metering. In related work, Itoh, Mitici, and Schultz (2022) proposed a time-varying fluid queue model for runway departures, showing that even with fixed runway capacity, temporal imbalances in arrival waves can produce cumulative delay buildups. These studies collectively demonstrate that delay events are temporally dependent and interconnected, reinforcing the value of dynamic modeling approaches.

The present study builds on these methodologies by integrating regression-based delay estimates into a simplified point process framework nested within the context of LAX departures. The two-stage design—predicting airport-induced delays from operational variables, then simulating their temporal propagation—extends prior research by situating delay contagion analysis within the specific operational environment of LAX. This combined approach seeks to bridge the gap between static predictive modeling and dynamic simulation, providing new insight into localized congestion dynamics within the context of LAX.

Methodology

Data processing

From each matched arrival–departure pair, derived features were constructed. Arrival delay was defined as the difference between actual and scheduled arrival times, but was set to zero if negative to avoid offsetting positive departure delays. This follows standard practice in delay analytics, where early arrivals are treated as having no delay rather than as negative delays. Departure delay was defined as the difference between actual and scheduled departure times, but was similarly set to zero if negative.

The target variable, Airport Delay, was defined as departure delay minus arrival delay, representing the added (or subtracted) component of the delay throughout the passage at LAX.

It is important to distinguish this from Turnaround Time, which measures the elapsed minutes between actual arrival and actual departure. Turnaround time is not itself a measure of delay but rather an operational interval that influences airport delay. Additional predictors included turnaround time, computed as the elapsed minutes between actual arrival and the scheduled departure time, and departure hour, extracted from the hour component of the scheduled departure time to capture potential diurnal patterns in congestion. To improve data quality, outliers were removed: records with implausible turnaround times shorter than 20 minutes or longer than 360 minutes were excluded, as such values likely reflected data entry errors or atypical operational scenarios. These thresholds were selected because turnarounds under 20 minutes are operationally infeasible and usually indicate data errors, while those longer than 360 minutes typically correspond to overnight stays, extended maintenance, or repositioning. This choice is consistent with exploratory analysis of the dataset and prior delay analytics literature. Additionally, flights that remained overnight at LAX and departed on a different calendar day than their arrival were excluded to ensure consistency in turnaround and delay calculations. Flights with missing or invalid timestamps were also dropped to prevent biases in model fitting. The dataset was obtained from the Aviationstack API, covering 13 operational days in June 2025.

Modeling

The Ordinary Least Squares (OLS) regression model, which assumes a linear relationship between predictors and the response variable and estimates this relationship by minimizing the sum of squared residuals, was then fit to predict airport delay using arrival delay, turnaround time, and departure hour as independent predictors. (Montgomery, Peck, and Vining 45) These predictors were selected because prior research identifies late arrivals and short turnarounds as strong drivers of departure delay (AhmadBeygi et al. 347), while departure hour captures congestion patterns that vary systematically across different times of the day (Sandhu and Liang 1340) This model was selected for its interpretability and its established use in the delay modeling literature for quantifying the marginal effects of operational variables. The resulting regression specification is given as:

$$\text{AirportDelay}_i = \beta_0 + \beta_1 \cdot \text{ArrivalDelay}_i + \beta_2 \cdot \text{TurnaroundTime}_i + \beta_3 \cdot \text{DepartureHour}_i + \epsilon_i \quad (1)$$

Where:

- **ArrivalDelay** (minutes) represents the delay at arrival, set to zero if negative.
- **TurnaroundTime (TT)** (minutes) is the elapsed time between actual arrival and actual departure.
- **DepartureHour (DH)** (0-23) is defined as the hour of scheduled departure.

The coefficients 1, 2, and 3 represent the marginal effect of each predictor on airport delay, conditional on the values of the other variables. The relationship between predicted and actual airport delays was visualized using a scatter plot, with the 45-degree reference line indicating perfect prediction alignment. This diagnostic plot provided a quick assessment of model performance and potential bias patterns.

Model evaluation was conducted via train–test data splits (Pedregosa et al. 2012), where the cleaned dataset of individual flight records was randomly divided at the flight level. A random 80% of the flights were assigned to the training set and the remaining 20% to the testing set. This approach meant that flights in the training and testing sets could share the same arrival dates, but ensured that the model had access to a representative sample of the entire operational period during training. Random splitting at the flight level is a common approach in predictive modeling when the objective is to evaluate overall predictive accuracy rather than day-specific generalization, although it does not account for potential correlations between delays of consecutive flights. Model performance was evaluated using the coefficient of determination (R^2) and the root mean squared error (RMSE) on the test set, which together indicate whether the model provides sufficient explanatory power and predictive accuracy.

All modeling was conducted in Python using scikit-learn's LinearRegression class. Model performance was evaluated using two standard metrics: the coefficient of determination (R^2) and the root mean squared error (RMSE). R^2 measures the proportion of variance in the target variable explained by the predictors, while RMSE quantifies the typical prediction error in minutes.

Although the Stage 1 regression offered quantitative insight into how arrival delay, turnaround time, and departure hour influence airport-induced departure delays, it treated each flight as an independent observation. In reality, operations at a high-capacity hub such as LAX are highly interconnected: a single late arrival can block a gate, delay multiple departures, and create ripple effects that spread through tightly sequenced arrival–departure flows. Such interdependencies mean that delays are not purely isolated events, but can cluster and propagate over time.

To capture this temporal dimension, Stage 2 applies a self-exciting point process model (Hawkes process), which is designed to represent events that influence the likelihood of future events occurring nearby in time. The predicted airport delays from Stage 1 are used as inputs for defining delay events and quantifying how one disruption increases the probability of subsequent delays within a given time window. Using predicted delays, rather than the raw observed delays, helps approximate the airport-induced component of disruptions at LAX, filtering out upstream disturbances inherited from prior flight legs.

A Hawkes process is a stochastic model in which the occurrence of one event temporarily increases the probability of subsequent events. Its key element is the *conditional intensity function* $\lambda(t)$, which specifies the instantaneous expected rate of event occurrence at time t , conditional on the history of previous events:

$$\lambda(t) = \mu + \sum_{t_i < t} \alpha e^{-\beta(t-t_i)} \quad (1)$$

where μ denotes the baseline delay rate, t_i is the time of a prior delay event, α measures the extent to which a delay increases the likelihood of subsequent delays, and β controls the exponential decay of this influence over time. In operational terms, α captures the contagion strength of delays, while β determines how long the effect of a prior delay persists.

In this study, a delay event is recorded whenever the airport-induced delay for a flight exceeds five minutes. The event time is defined as the actual departure timestamp (UTC), and the event magnitude is derived from the Stage 1 predictions. This construction ensures that the model captures propagation mechanisms internal to LAX operations, rather than simply reproducing inherited upstream delays. The Hawkes process was trained via maximum likelihood estimation, and its performance was evaluated using log-likelihood and the Akaike Information Criterion (AIC).

Results

Stage 1: Regression Model Performance

The Stage 1 regression model's predictive performance was evaluated on the held-out test set using two standard metrics. R^2 (coefficient of determination) was approximately 0.04, meaning that only about 4% of the variability in airport-induced departure delays was explained by the model. Figure 1 visualizes the relationship between predicted and actual *AirportDelay* on the test set. Most points cluster near zero delay, while the wide scatter for outlier flights highlights substantial unexplained variability. Points are colored by residual sign (positive or negative) to better illustrate systematic patterns of over- and under-prediction.

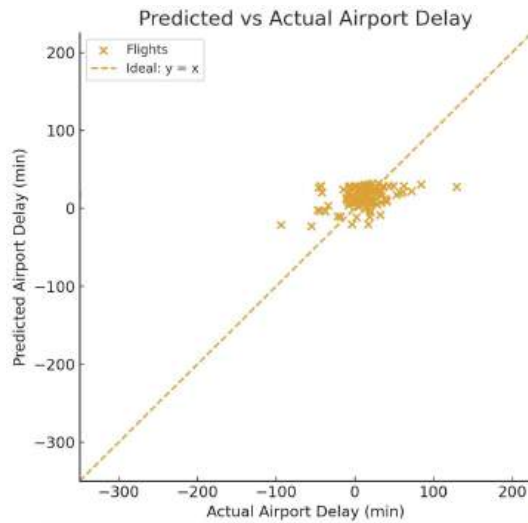


Figure 1: Predicted vs Actual *AirportDelay* on the test set. The dashed line denotes the ideal $y = x$ relationship.

Table 1 reports the estimated coefficients, standard errors, and significance levels from the OLS regression. The standard error measures the precision of each coefficient estimate, with smaller values indicating greater reliability. The p-value tests the null hypothesis that a coefficient is zero (no effect), where $p < 0.05$ is conventionally considered statistically significant. Significance levels are denoted as: $p < 0.001$, $p < 0.01$, $p < 0.05$, and (ns) not significant. These statistics were estimated using standard OLS procedures, which assume errors are independently and identically distributed.

Predictor	Coefficient (β)	Std. Error	p-value	Significance
Intercept	-18.21	9.391	0.05275	(ns)
ArrivalDelay	-0.96	0.168	0.00000	***
TurnaroundTime	-0.003	0.008	0.71978	(ns)
DepartureHour	2.648	0.668	0.00008	***

Table 1: Estimated coefficients, standard errors, and significance levels from the OLS regression.

The coefficients show that ArrivalDelay ($\beta = -0.96$, $p < 0.001$) and DepartureHour ($\beta = 2.648$, $p < 0.001$) were statistically significant predictors of *AirportDelay*. In contrast, TurnaroundTime ($\beta = -0.003$, $p = 0.72$) and the intercept ($\beta = -18.21$, $p = 0.053$) were not significant at the 5% level. The signs of the coefficients indicate that later scheduled departure hours are associated with larger delays, while longer turnaround times did not have a measurable effect in this specification.

Stage 2: Point Process Simulation of Delay Propagation

While the Stage 1 regression quantified static relationships between operational variables and airport-induced delays, it did not capture the temporal dependencies between delay events. In reality, at a high-capacity hub such as LAX, a single delayed departure can cascade through tightly sequenced operations, disrupting subsequent flights. To capture this dynamic behavior, Stage 2 applies a self-exciting point process (Hawkes process) to model the temporal clustering of delay events.

Table 1 reports the parameter estimates obtained from fitting the Hawkes process model (defined in the methodology section) to the training dataset. Parameter estimates, units, and interpretations are summarized below.

Parameter	Estimate	Unit	Interpretation
μ	6.6×10^{-5}	s ⁻¹	Baseline intensity
α	1.36×10^{-4}	—	Excitation magnitude
β	1.84×10^{-4}	s ⁻¹	Decay rate

These estimates correspond to an influence half-life of approximately 62.8 minutes, meaning that a single delay increases the likelihood of subsequent delays by an amount proportional to α , with its influence decaying by half after roughly one hour.

Figure 2 illustrates the estimated delay intensity $\lambda(t)$ produced by the Hawkes process model over 1–13 June 2025 at LAX. The intensity function was computed from predicted airport-induced delays, with peaks indicating periods when delay events clustered in time. Notably, elevated afternoon and evening peaks align with known high-demand departure periods at LAX, reflecting the model’s ability to capture the temporal propagation of disruptions.

Figure 3 shows the distribution of time-rescaled inter-event intervals. If the Hawkes process with an exponential kernel fully captured the temporal dependencies, the rescaled intervals would follow a unit exponential distribution. The observed deviations from this ideal distribution indicate that some residual temporal dependencies remain, suggesting areas for future model refinement.

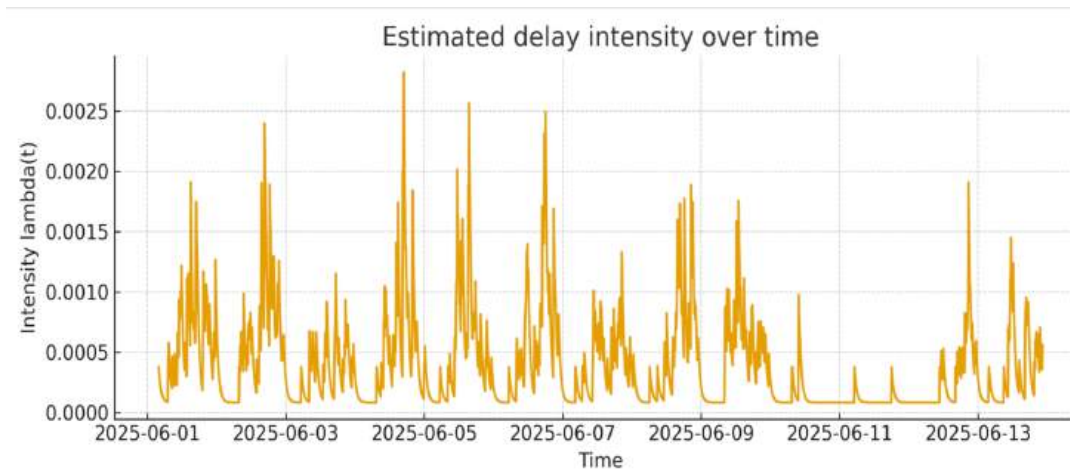


Figure 2: Estimated delay intensity $\lambda(t)$ over 1–13 June 2025 at LAX. Peaks correspond to periods of stronger clustering of departure delay events.

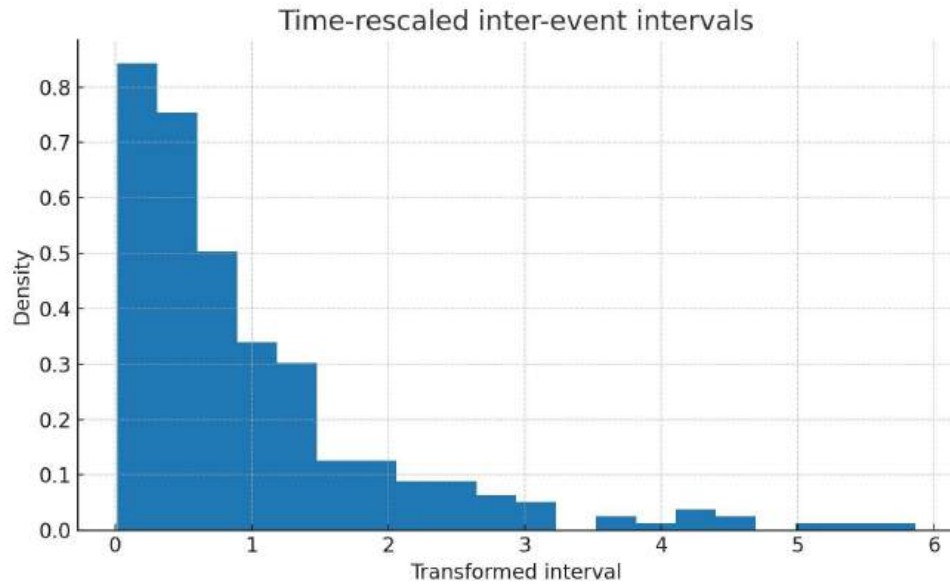


Figure 3: Time-rescaled inter-event intervals. Departures from the ideal unit exponential distribution indicate residual temporal dependencies not fully captured by the exponential kernel.

Discussion

The Stage 1 regression analysis, while exhibiting limited predictive accuracy for exact delay magnitudes ($R^2 \approx 0.04$), still provided valuable directional insight into how operational variables shape airport-induced departure delays. Table 1 reports the estimated coefficients, showing that ArrivalDelay has a statistically significant negative effect on subsequent departure delays ($\beta = -0.96$, $p < 0.001$), suggesting the presence of absorption mechanisms that reduce the extent to which late arrivals propagate further disruption. In addition, DepartureHour emerges as a significant positive predictor ($\beta = 2.65$, $p < 0.001$), indicating that departures scheduled later in the day are more likely to experience additional delays due to congestion and peak-hour traffic pressures at LAX. By contrast, TurnaroundTime ($\beta = -0.003$, $p = 0.72$) was statistically insignificant, suggesting that variation in ground time between arrival and departure did not exert a measurable effect on departure delay propagation in this dataset.

A deeper interpretation of these coefficients highlights important operational dynamics. The negative coefficient for ArrivalDelay reflects the ability of airport operations to absorb or mitigate incoming delays, possibly through prioritization of late-arriving aircraft or other ground-handling adjustments. Conversely, the positive coefficient for DepartureHour underscores the structural influence of diurnal congestion patterns, where resource competition during peak traffic periods exacerbates departure delays. The lack of significance for TurnaroundTime suggests that turnaround processes at LAX are sufficiently standardized or buffered to prevent systematic effects on departure delay outcomes.

The modest explanatory power is unsurprising given the stochastic nature of airport operations, where exogenous factors such as weather conditions, air traffic control interventions, and gate allocation conflicts introduce variability beyond the reach of a static regression

framework. This limitation motivates the need for a complementary approach that explicitly captures temporal dependencies between delay events and enhances the model's ability to handle stochastic shocks and outliers.

Stage 2 proposed an attempt to address this gap by employing a self-exciting point process model to quantify the clustering behavior of delays in time. The estimated half-life of approximately 62.8 minutes indicates that a single delay increases the probability of subsequent delays by about 15–20% within the following hour. The fitted intensity function revealed pronounced afternoon and evening peaks, corresponding to high-demand departure waves, and pinpointed operational periods most susceptible to cascading disruptions. This temporal perspective extends beyond the baseline relationships identified in Stage 1, offering a more operationally relevant depiction of how delays propagate in practice.

From a practical standpoint, mitigation strategies should be both targeted and time-sensitive. Interventions such as dynamic gate reassignment, flexible turnaround scheduling, and real-time air traffic flow adjustments are most effective when deployed during the high-intensity periods identified by the model (Chatterji and Sridhar 4). By integrating regression-based predictors with temporal interaction modeling, this two-stage framework moves beyond static prediction to provide actionable insight into the mechanisms and timing of delay propagation at LAX.

Conclusion

This study examined delay propagation at Los Angeles International Airport through a two-stage framework that combined predictive modeling with temporal interaction analysis. Together, the two stages present a more complete picture of delay formation and propagation at LAX. The regression model results showed that ArrivalDelay had a statistically significant negative effect on departure delays ($\beta = -0.96$, $p < 0.001$), while DepartureHour was a statistically significant positive predictor ($\beta = 2.65$, $p < 0.001$). By contrast, TurnaroundTime was not statistically significant ($\beta = -0.003$, $p = 0.72$). These results highlight the dual role of operational absorption effects, which can dampen the impact of late arrivals, and diurnal congestion patterns, which amplify departure delays during peak traffic periods. The point process model, in turn, quantified temporal clustering and revealed that a single disruption increases the likelihood of subsequent delays for up to an hour, with the effect strongest during afternoon and evening peaks. This combined approach offers actionable insights for airport management: interventions such as flexible turnaround scheduling, dynamic gate reassignment, and targeted air traffic flow adjustments can be strategically timed to periods of heightened vulnerability. Looking ahead, this framework could be expanded by incorporating additional predictors such as weather data, aircraft type, and passenger connection patterns, as well as by testing alternative kernel functions for the point process model. These enhancements would further refine the ability to anticipate, handle outliers, and mitigate cascading delays, contributing to more resilient and efficient airport operations.

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The Impact of Coaching Style on the Anxious States of Adolescent Female Athletes in the United States: A Literature Review By Molly Gordon

Abstract

All throughout history, teenage girls in sports have faced challenges with their mental health. Lately, as more female athletes have opened up about their struggles, there has been growing attention on how much coaches can affect their athletes' mental well-being. Since teenagers are especially sensitive to what adults in authority say and do, the behavior of coaches can have a big impact on how young female athletes feel. Studies show that different coaching styles can either help or harm an athlete's success and overall mental health. Supportive and democratic coaching styles often create positive relationships between coaches and athletes, making sports more enjoyable and encouraging girls to keep participating. On the other hand, strict and authoritarian coaching styles can increase stress and anxiety. This literature review will look at how coaching styles influence the anxiety levels of middle-adolescent female athletes in the United States.

Introduction

Participation in sports is a crucial part of adolescent development and promotes both physical and mental well-being. Adolescents who participate in sports often face fewer challenges with their mental health and have more optimistic outlooks on life (Cumming et al. 515). These activities foster discipline, teamwork, and resilience, all of which contribute to a profoundly positive impact on young athletes. Sports can be a great way for young girls to release stress, stay physically active, improve their sleep, and become more comfortable in their bodies (Vakrilova Becheva et al. 751).

While sports have been found to be beneficial for female athletes, research also suggests that engaging in sports increases their vulnerability to various mental health disorders. Girls in sports are susceptible to mental health struggles due to long and challenging workouts, injuries, high and unrealistic expectations, and pressure from parents and coaches (Cumming et al. 515). For example, when adolescents worry about making their parents and coaches proud of their performance in sports, it increases their anxiety levels. Studies have shown that as many as 16.9% of adolescent athletes have struggled with their mental health throughout their athletic careers (Long et al. 193). Anxiety is a mental health disorder commonly found in athletic girls (Clark et al. 1). This disorder can put adolescents at a disadvantage in the development of both their mental and social well-being (Peterson 185). It is vital to understand the causes of mental disorders and ways to prevent them to protect female athletes and ensure wellness, success, and continuation of sport participation.

Researchers continue to examine coaching's influence on athletes' mental health outcomes. They have found that coaches potentially play the largest role in the development of mental health disorders in adolescent female athletes, due to the coach being the primary authority figure of the team and their influence over an athlete's ability to play their sport.

Pressure, punishments, and public criticism from coaches only exacerbate the nerves that most athletes already feel from being in a competitive environment (Gomez-Lopez et al. 592).

It is important, however, to note that plenty of coaches create healthy and safe climates for their athletes to flourish and prosper in their sport. Healthy coaching methods are important to ensure athletes are supported and uplifted by their coaches to reduce the rate of mental disorders and support the growth and progress of athletes (Hagerty and Felizzi 67). With the increasing number of girls in sports, it is more important than ever to educate coaches on the proper coaching techniques so that a new generation of female athletes can succeed with limited mental health issues (Knell et al.). This literature review discusses the pros and cons of various coaching styles and their mental health-related effects on female athletes. It will also encompass ways to improve coaching and support athletes to promote a healthy sense of well-being.

Literature Review

Impact of Sports on the Mental Health of Adolescent Female Athletes

Physical activity positively affects adolescents by reducing rates of anxiety and depression while increasing self-assurance (Ghiami et al. 34). Sports and exercise are a great way for adolescents to relieve stress, maintain physical health, and boost their confidence (Vakrilova Becheva et al. 752). In a study done on female high school basketball players and gymnasts, researchers found that student-athletes had significantly lower rates of depression and anxiety than their non-athlete counterparts (Cumming et al. 516). Participation can be uplifting for young athletes in various ways. Sports expand adolescents' social lives as they can create friendships with others similar to them and in the same sport. Playing sports can also be a time for young athletes to focus on their physical activity rather than the many other stressors that come with being an adolescent.

Another positive outcome of sports participation in young athletes is keeping their physical health in check, and in turn decreases their likelihood of developing mental health disorders. For children and adolescents, exercise is a crucial part of ensuring they carry out healthy lifestyles (Trost & Loprinzi 162). Typically, adolescents participating in sports, excluding sports with a focus on aesthetics (performance is judged both on technicality of skills and artistry and appearance), have fewer cases of body dysmorphia and eating disorders (Cumming et al. 516). Increased physical movement, which often accompanies a healthier diet, is also a major aspect in treating and preventing obesity (Nelson et al. 360). As sports promote healthier eating and include physical activity, non-athletes tend to struggle with their weight more than athletes. Adolescents who are classified as overweight tend to be bullied more often and more harshly than children with normal weights. The bullying these children endure can potentially lead to low self-esteem, waning confidence, anxiety, and depression. This suggests that adolescents not participating in sports indirectly increase their chances of developing mental health disorders (Janssen et al. 1187).

While this does not apply to every adolescent, there is evidence from many studies to support that children who do not participate in sports tend to face mental health struggles more than their athletic counterparts. Conversely, children who engage in sports tend to be in good physical and psychological condition, endure fewer medical issues, and often lead healthier lives through adulthood, both physically and mentally (Cumming et al. 516).

However, despite the many benefits of sports participation for adolescents, certain sports put young female athletes at a greater risk for developing mental disorders. Sports such as gymnastics, dance, and cheerleading that focus on the aesthetic aspect put more pressure on athletes to look a certain way. The pressure to change their bodies often results in these athletes reporting higher rates of anxiety, body dysmorphia, and eating disorders. One study found that athletes in individual and aesthetic sports had higher levels of social physique anxiety when compared to athletes in team sports. Social physique anxiety is defined as the stress people undergo when their bodies are observed or judged (Fishback). Girls in this category of sports tend to be judged by coaches and themselves on their bodies, causing greater anxiety surrounding the subject of their appearance. These young girls are also often taught to believe that the smaller they are, the better they will be at their sport, naturally leading to disordered eating behaviors and loss of self-confidence. To counter this, coaches must avoid pressuring athletes into changing their bodies to benefit their sports careers (Fishback).

Similarly, the sheer pressure on adolescents in competitive sports can be a trigger for anxiety. Whether it is the demand to progress to the next level or win at a competition, young female athletes are likely to experience sport performance anxiety. The tendency to feel threatened or scared when in a competitive sports environment, known as sport performance anxiety, can be detrimental to adolescent athletes' self-esteem and motivation for their sport (Smith et al. 126). Sport performance anxiety often leads to athletes performing below their potential due to their fear, since anxiety regarding sports competitions can be felt both somatically and cognitively (Sridana et al. 241), per the multidimensional anxiety theory. Sport performance anxiety can affect both the mind and body of the athlete, making it crucial to recognize its development and treat it before the athlete becomes burnt out. Furthermore, in adolescents, anxiety can lead to the development of other mental health disorders such as depression (Cole et al. 451). In fact, studies have reported that "over 90% of individuals with anxiety disorders have a lifetime history of other psychiatric problems", underscoring the need to combat anxiety in young female athletes (Kaufman and Charney 69). Athletes, coaches, and parents must understand the triggers for sports anxiety to avoid unnecessary stress and potential injury to the athlete, specifically the way different coaching styles can affect athletes' worries.

Coaching Styles

Just as every athlete is unique, coaches differ in the methods and techniques they use. Coaching methods are categorized into four distinct styles: democratic, autocratic, laissez-faire, and holistic.

The democratic coaching style entails a balance between the coach and the athlete (Maryville University). In this type of coaching, the athlete and coach share influence and collaborate when making decisions about practice and training (Sridana et al. 242). Athletes often enjoy being coached under a democratic style as they are given the power to contribute their wishes and opinions, but are still directed by the coach, who ultimately has authority (Maryville University). Democratic coaching is often beneficial for adolescent athletes because they are included in the decisions about their sports activity without the coach giving up too much power to the point that the sport loses structure and the roles of instructor and student become unclear.

Next, autocratic leadership is characterized by a demanding coach who controls every decision and aspect of the sport. Under an autocratic coach, athletes have little to no opportunities to input their ideas or preferences (Chawla and Sharma 201). This type of coaching can work successfully in some cases, such as when the coach is extremely educated and informed, but most often, athletes find the sport less enjoyable under their autocratic coach, which can contribute to feelings of stress and anxiety (Maryville University). Especially when coaching adolescents who are finding their voice and way in life, their thoughts and feelings mustn't be suppressed.

The laissez-faire coaching style refers to a coach who fails to supervise their athletes and often does not give them feedback on their performance (Chawla and Sharma 201). Under laissez-faire leadership, athletes have more influence than their coaches, who give them the power to make nearly all decisions in their sports experience. While this coaching technique allows athletes to become more independent and express themselves, it can have adverse effects when athletes lose motivation (Maryville University). For example, if an athlete is becoming uninterested in continuing the sport and their coach does not instruct them during practices, they are even more likely to not participate during training sessions and eventually drop out. Lastly, a holistic coach emphasizes their students' growth in every aspect, not just athletics. These trainers work to help their athletes both physically and mentally while promoting their well-being (Waeffler). Holistic coaches strengthen their students physically but do not neglect the fact that they are humans first and athletes second (Maryville University, 2021). They aim to teach their pupils life skills and values to use in the real world, along with sport-specific lessons to create well-rounded athletes.

Beyond these commonly categorized coaching methods, two additional styles-- authoritarian and autonomy-supportive coaching-- are often discussed within the framework of the Self-Determination Theory due to their significant influence on athlete motivation and well-being. An authoritarian coaching style includes a demanding coach who asserts their unchallenging power, has unreasonably high expectations, and scolds athletes who do not meet their standards (Cheng et al. 121). These coaches often focus more on establishing their dominance than actually training and helping their athletes succeed. They demand excellence from their students and correct them with negative feedback (Peterson 185). In addition to being controlling, authoritarian instructors often scream, humiliate, and punish their athletes for not

reaching their expectations, making adolescent athletes less inclined to form relationships with and trust their coaches (Marcone). Another outcome associated with authoritarian coaches in sports is the athletes losing their sense of autonomy (Brinton 5). Specifically, with young female athletes, when they are exposed to coaches who refuse to listen to their input, they feel a loss of control over their experience in sports. On the other hand, in specific cases, authoritarian coaching may help athletes succeed. Athletes may be inclined to listen to the demands of their coaches and exert maximum effort during training to avoid being reprimanded. Research has shown that strict authoritarian coaches led to athletes putting in more effort and contributed to them winning in competitions (Cheng et al. 122). Although this rigid coaching method may benefit some athletes by helping them win, overall, harsh, authoritarian coaching frequently results in young athletes losing their motivation for the sport.

The autonomy-supportive coaching style refers to coaches helping their athletes improve and succeed by motivating them. This technique aims to encourage young athletes to grow in their sport without harsh criticism and punishment (Hagerty and Felizzi 68). These coaching behaviors enable the athletes to have a say in their training program in order for them to build intrinsic motivation for the sport and enjoy participating in it (Jeong et al. 1). When young female athletes feel autonomy or a sense of control in their sport, they are more likely to find satisfaction in it. Another advantage of the autonomy-supportive coach is that they are more approachable than an authoritarian coach. These instructors allow for open communication with their pupils, provide constructive criticism, and make it clear they want their students to grow and not just win. These characteristics make the coaches more approachable, and their juvenile athletes feel comfortable voicing their opinions, leading to an overall more positive experience in their sport (Marcone). Finally, one of the most important aspects of autonomy-supportive coaching is the focus on the well-being of the athlete, even at the expense of athletic progress. These teachers understand the vitality of adolescents' mental health and how sports can both benefit and worsen it. Autonomy-supportive coaches motivate their athletes to succeed to create a healthy environment for them to flourish as individuals and as athletes without degrading them for their mistakes like an authoritarian coach (Peterson 187).

Impact of Coaching Methods on Anxiety of Female Adolescent Athletes

How a coach instructs their adolescent athletes can have a great impact on their mental health, specifically on their anxiety levels (Sridana et al. 242). Young athletes may view their coaches as highly influential, with the power to determine their athletic path. This can create an environment where the children feel the need to please their coach to progress in the sport, leading to fears about their future if they don't. In this way, coaches can both trigger anxiety in their athletes and reinforce it (Peterson, 188). Understanding how coaching style influences anxiety is essential for identifying methods that reduce stress while promoting success.

To start, democratic coaching overall tends to benefit athletes (Sridana et al. 241). Due to the positive instruction, open discussions, and shared influence during the decision-making process, athletes coached under the democratic style often feel comfortable and valued, leading

to reductions in their stress levels (Jawoosh et al. 1115). As one of the pillars of democratic coaching is a focus on the well-being of athletes, these coaches make an effort to boost their students' confidence. When adolescent female athletes are self-assured and feel comfortable with their skills, their anxiety tends to decrease, thereby enabling them to prosper and excel (Jimenez et al. 1).

On the other hand, research has shown that autocratic leadership produces a much greater anxiety response in athletic girls than democratic coaching (Cay et al. 295). Autocratic coaching, in which the instructor asserts their complete dominance over their students, typically leads to an environment of fear. Students are compelled to meet their coaches' often unrealistic expectations due to their anxiety about the outcomes if they do not. For example, autocratic instructors may threaten to prevent athletes from playing in games or demote them to a lower level in their sport if they do not meet their goals. Along with the fear of not impressing their coaches, young athletes under autocratic trainers also stress about their coaches' criticism. Their anxiety only grows as their teachers provide negative feedback, act on aggression, and yell and humiliate them (Jimenez et al. 2). This coaching style leads many athletes into a cycle of continuous anxiety. Symptoms of stress can have severe effects on the body, hindering athletes' sports performance. Then, with athletes performing under par, their strict, demanding coaches only have more negative feedback to give (Oberle and Schonert-Reichl 30). In all, autocratic coaching methods typically cause increases in the anxiety of female adolescent athletes.

Next, the laid-back and sometimes neglectful *laissez-faire* coaching style can also increase the anxiety levels of young girls in sports. While this style of coaching does not create a threatening environment, it often leads to athletes feeling unprepared in competitive environments (Maryville University). Since these coaches hand over much of their responsibilities to the athletes, young girls without the education to coach themselves have to both teach themselves their skills and master them before competing. This neglect can trigger stress in students who wish to excel in competition but have not had the correct training and, therefore, are at a disadvantage (Chawla and Sharma 201). *Laissez-faire* coaching may escalate anxiety by leaving athletes to "coach" themselves, leading to feelings of unpreparedness.

Research has shown that athletes training under holistic coaches typically show fewer signs of anxiety than other techniques (Waeffler). These teachers appreciate that their students are not just athletes. They acknowledge that they are children too, who need to be treated and taught with care and respect (Maryville University). Due to this understanding, holistic coaches often aim to put less pressure on their athletes and enable them to enjoy their sport, leading to reduced stress and anxiety. Along with limiting their sports-related stress, holistic instructors teach their students life lessons for them to use outside of their athletic careers. These social skills and values can help young students in the real world, possibly avoiding additional stress in that aspect as well (Waeffler).

Authoritarian coaching often induces and increases stress in adolescent female athletes (Hagerty and Felizzi 69). Emotional abuse and extreme pressure imposed on girls by their sports instructors is often a major source of anxiety. They fear the demands, punishments, and criticism

that often come with an authoritarian coach. The controlling environment can make the children feel coerced to perform to the expectations of their teachers out of extreme fear (Peterson 190). The anxiety that students experience during practice can have both somatic symptoms and cognitive effects, leading to worsening performance and focus. Subsequently, those effects can cause athletes to underperform during competitions and therefore increase their stress levels even more (Ramis et al.). Another anxiety-producing factor of this coaching style is the removal of power from the athlete. Authoritarian coaches take full control of decisions, taking autonomy away from the players. Studies have shown that in adolescent females, a decrease in autonomy is directly associated with an increase in anxiety (Cheng et al. 122). Athletes become more anxious when they are forced to follow the demands of their strict coaches, with the looming threat of punishment if they do not.

Lastly, as opposed to authoritarian coaching, which often increases the nerves of young athletes, autonomy-supportive coaching tends to decrease their anxiety and boost their comfort and confidence (Hagerty and Felizzi 70). Because of their focus on the wellness of athletes, autonomy-supportive methods have been seen to improve the mental health and reduce the fears of players. It is paramount that adolescents receive guidance and constructive feedback to allow them to grow in and out of their sport. This coaching style supports athletes' well-being and provides them with the ability to make choices for their training (Jeong et al. 1). The sense of self-efficacy enables girls to make decisions that feel safe and comfortable for them to eliminate their stress. Autonomy-supportive coaching also builds intrinsic motivation in young females, meaning they wish to continue their sport because they enjoy it and not due to outside factors. This too reduces their stress as they play their sport for fun as opposed to continuing it to please their parents or coaches, for example (Jeong et al. 1). Unlike authoritarian coaches, autonomy-supportive coaches reduce anxiety by promoting choice and self-confidence.

The Self-Determination Theory

The self-determination theory provides a framework for explaining athletes' motivation to continue their sport, and the reasons other athletes quit their sport. Principles from the self-determination theory are vital in understanding ways to successfully encourage young females to engage in physical activity and help them find the motivation to continue. This theory is crucial to understand to benefit adolescents both physically and mentally through sports participation. The self-determination theory states that humans have three basic psychological needs: autonomy, relatedness, and competence. Autonomy refers to acting voluntarily and based on one's own sense of self. Relatedness entails feeling connected and united with the community one is involved in. Competence is defined as having the ability to perform successfully. In sports, when these three needs are met, athletes tend to have the motivation to continue participating in their sport. Conversely, when all or some of the psychological needs are neglected, athletes are more likely to drop out (Calvo et al. 677). Democratic and autonomy-supportive coaching styles directly fulfill these three needs, further supporting their positive effect on adolescent athletes.

Self-determination theory also focuses on intrinsic and extrinsic factors to explore human motivation. One sub-theory of the self-determination theory is the Cognitive Evaluation Theory, which describes these two types of motivation. Intrinsic motivation is the drive to continue an activity for the pleasure and satisfaction of doing it without regard to external consequences. On the other hand, extrinsic motivation arises due to outside factors like the rewards that may come from the activity or the punishments that can be avoided by doing it, instead of the pleasure that comes from simply doing the activity. Research has shown that adolescent athletes are often motivated in their sport by a combination of intrinsic and extrinsic motivation (Vallerand and Losier 143). However, when athletes remain in their sport solely due to extrinsic motivation, they typically lose enjoyment and wish to quit when the motivator is removed, such as an athlete who only plays their sport to win trophies, who then begins to lose at competitions and no longer wants to compete (Nogg et al.). These findings display the necessity for coaches, parents, and athletes to create an environment in which athletes find pleasure in participating in their sport to avoid dropout.

Conclusion

To support the emotional and mental well-being of young female athletes, effective sports coaching is crucial. As coaches are the primary authority figure in youth sports, their students look to them for guidance and are directly affected by their superiors' coaching methods (Sridana et al. 241). Adolescence is a common time for females to struggle with their confidence and, unfortunately, possibly develop anxiety, depression, or other mental health disorders due to physical and social changes. Sports, however, can be a great outlet for young girls to feel more comfortable in their bodies, stay active, and branch out socially (Vakrilova Becheva et al. 752).

While sport participation comes with many benefits for young minds and bodies, certain aspects can actually spark or amplify existing mental health challenges. Pressure from parents and coaches, harsh criticism, and fear of failure in competition can all increase anxiety in female athletes (Mottaghi et al. 69). Due to the coach's major influence over the wellness of their athletes, it is essential to understand the beneficial and detrimental coaching styles and their effect on the anxiety levels of athletic girls.

Research highlights the pros and cons of various instructing techniques, detailing their impact on stress for athletes. Democratic coaching allows players and coaches to collaborate and compromise in decision-making, empowering athletes and decreasing their anxiety while increasing their intrinsic motivation for continuing their sport (Maryville University). The autocratic leadership style characterizes coaches who assume complete control over their athletes, often causing them to struggle more due to their fears of negative criticism, punishment, and the immense pressure put on them (Sridana et al. 241). On the other hand, laissez-faire coaches often lack leadership skills, delegating many responsibilities to athletes, causing increased stress for young girls who are left unprepared and forced to 'coach' themselves (Chawla and Sharma 201). Holistic coaches recognize their students as individuals beyond their athletic roles, emphasizing supporting their pupils physically and mentally to create healthy and

successful athletes (Waeffler). Per the self-determination theory, the authoritarian method includes a controlling coach with strict rules, unrealistic expectations, and harsh consequences for not meeting them, creating a climate of fear and anxiety in athletes (Ramis et al.). Conversely, the autonomy-supportive coaching style focuses on creating an environment where athletes can make their own decisions with the coach's support, giving young females a sense of control and self-efficacy (Peterson 193).

One academic theory related to this literature review is the self-determination theory, which explains the reasoning behind athletes dropping out of their sports and the motivation other athletes have for continuing their athletic careers (Jeong et al. 1). One sub-theory, called the Basic Psychological Needs Theory, describes the three basic psychological needs of humans: autonomy, relatedness, and competence. When these three needs are met, athletes are more motivated to continue their sport, but when all or some of the needs are neglected, girls are more likely to quit (Calvo et al. 677). Another subtheory of the self-determination theory, the Cognitive Evaluation Theory, explores intrinsic and extrinsic motivation, describing how most adolescent athletes are motivated by both factors to continue participating in their sport (Vallerand and Losier 143). The findings from the self-determination theory are key to encouraging young girls to continue pursuing their sports and reducing the rate of athlete dropout.

To conclude, with the growing number of female adolescents participating in sports, it is more important than ever to ensure that coaches have proper training to support happy and healthy athletes. Various courses and programs exist to instruct coaches on social skills, sport-specific training, and athlete well-being. One educational training program is called Coach Effectiveness Training. This learning initiative teaches coaches specific skills to strengthen and grow relationships with their athletes, reduce stress in students, and enhance team unity (Smith et al. 126). Another method of coach training is through hands-on experience. Research has shown that observing coaches, discussion groups with coaches from different programs or different sports, and having previous experience playing sports are other informal techniques that can help coaches understand their athletes and improve their teaching abilities (Lemyre et al. 191). Ultimately, coach training programs that emphasize athlete well-being may be one of the most effective ways to reduce anxiety in adolescent female athletes.

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Sex-Specific Responses to Music Therapy in Older Adults With Cognitive Impairment

By Hikaru Shibata

Abstract

As neurodegenerative diseases become increasingly prevalent in today's aging society, Alzheimer's disease (AD) is known to be the most common among them. Having no cure for the disease, music therapy (MT) has recently become widely recognized as a promising non-invasive therapeutic approach towards improving cognitive and behavioral aspects of individuals with cognitive impairment. Research has shown that music can influence brain structure, regulate the immune system, and evoke emotional states as well as autobiographical memories. Given that more females are being diagnosed with AD than males, studies have identified biological sex differences, such as hormones that contribute to the development of these diseases, along with differences in the processing/perception of music between sexes. Although research in these areas has been conducted, there is a limited understanding of the sex differences in the effects of MT, particularly in cognitively impaired older adults. To investigate whether MT interventions yield varied results between males and females, this study utilizes a publicly available dataset from a previous study as the basis for its analyses. Multiple cognitive and behavioral tests are performed both before and after the MT intervention to identify patterns and the significance of improvements. The study focuses on four outcome measures: the Music Cognitive Test (MCT), Montreal Cognitive Assessment (MOCA), Cornell Scale for Depression in Dementia (CSDD), and Satisfaction With Life Scale (SWLS). Findings reveal that females demonstrated significant improvements in MCT, MOCA, and CSDD scores upon MT, while males exhibited no significant changes. SWLS scores did not show significant improvements for either sex. Therefore, this study highlights the sex differences in the effectiveness of MT that were previously unexamined in the original research. However, a limitation was the underrepresentation of males in the sample size, which could have biased the results observed in females. This investigation suggests future development of sex-specific MT interventions in enhancing the effectiveness for both male and female cognitively impaired individuals.

Keywords music therapy; sex differences; cognitive impairment; cognition; behavior

Introduction

Impact of Aging on Cognitive Function

In our modern world, as life expectancy continues to grow globally, it is often associated with an increase in age-related neurodegenerative diseases (Brito et al.). Neurodegenerative diseases such as Alzheimer's disease (AD) pose a major health issue with more than 50 million people affected, and expected to triple to 152 million in 2050 if effective solutions are not found (Livingston et al.). Aging can lead to declined cognitive functions as well as cause risks of developing neurological disorders (Brito et al.). Significant changes in cognition include

decreased processing speed, working memory, and executive cognitive functions (Murman). Altered neuronal structure correlates with changes in brain structure and function, increasing the rate of neuronal loss and damage, as well as cognitive impairments, which limit many people's ability to conduct everyday activities (Murman). Loss of synaptic complexity and decreased white matter volumes in the brain due to aging also lead to impaired brain plasticity and function (Harada et al.; Murman). A study revealed that increased prefrontal activity was linked to lower cognitive performance. When observed in aged rats with cognitive impairment, irregular activation was found in cortical regions and hippocampal subregions (Haberman et al.). Additionally, the motor-associated regions are also affected through aging, specifically altering cerebellar activity during spatial navigation or motor learning (Ramanoël et al.).

Music and the Brain

The human brain is highly adaptable to the environment, demonstrating structural brain changes and plasticity through long-term music training (Hyde et al.). Musicians begin acquiring complex motor and auditory abilities from early childhood and continue to practice these skills consistently throughout their careers (Gaser and Schlaug). When professional keyboard players and a matched group of amateur musicians and non-musicians were compared, differences in gray matter volume were found in motor, auditory, and visual-spatial regions of the brain (Gaser and Schlaug). Prolonged practice and repetitive use of specific brain regions have led to structural adaptations within the brain (Gaser and Schlaug).

Other studies have also shown differences in brain structures between musicians and non-musicians. The corpus callosum (CC) is the major interhemispheric nerve fiber tract that connects the two hemispheres of the brain, allowing communication (Schlaug et al.). The anterior half of the CC was shown to be significantly larger in musicians who began musical training before the age of seven (Schlaug et al.). Hence, this suggests altered interhemispheric interaction and possible hemispheric variation of sensorimotor regions (Schlaug et al.).

In addition to the long-term brain structural changes induced by music, it can also produce immediate effects on an individual's behavior and emotional state. Listeners perceive genuine emotional responses evoked from music (Lundqvist et al.). Through analyzing data from self-reported emotion, facial muscle activity, and autonomic activity while listening to happy or sad popular music, results were coherent in all experiential, expressive, and physiological aspects of emotional response (Lundqvist et al.). The listeners experienced the same emotions evoked by the music, such as increased happiness/less sadness in uplifting music, as well as more zygomatic facial muscle activity (Lundqvist et al.). Therefore, music has the power to induce emotional responses from the brain.

Effects of Music Therapy (MT)

Research by Matziorinis and Koelsch suggests that among the various types of long-term memory, including semantic, episodic, and procedural memories, musically evoked memories are independent of the other elements of the memory store. Although a patient with AD can

experience severe memory problems, they can still recall music, which can promote the recall of episodic memories, even when the music is unrelated to the events being recalled (Matziorinis and Koelsch; Chevreau et al.). As hormones such as dopamine are released through the endocrine system in response to music, the neuroendocrine stress response can also be affected, leading to changes in the regulation of the immune system (Matziorinis and Koelsch). The use of music as a therapeutic method may potentially reverse the ‘brain age’ of patients by evoking neurogenesis, restoring hippocampal volume, and delaying neurodegeneration (Matziorinis and Koelsch).

Apart from the cognitive benefits, MT has been shown to positively impact various behavioral and psychological aspects in patients with AD and other neurological disorders. Music has been clinically proven to reduce depression and anxiety levels, while enhancing mood, autobiographical recall (Chevreau et al.), and self-expression, which are found to be particularly effective after trauma (Ramaswamy et al.; Matziorinis and Koelsch). Other studies have found that music can stimulate the parasympathetic branch of the autonomic nervous system, as well as reduce excessive activation of stress responses (Ramaswamy et al.). Therefore, the ability of MT to enhance both cognitive function and mental well-being demonstrates its potential as a safe and promising alternative approach towards improving symptoms associated with AD (Lyu et al.; Matziorinis and Koelsch).

Sex Differences

Among the Americans with AD, two-thirds are women, highlighting variances between the sexes (Kolahchi et al.). Women have also been shown to have significantly faster age-related cognitive decline than men (Li and Singh). Despite the limited understanding of the underlying mechanisms that cause AD, factors such as biological sex, genetic predispositions, hormones, and environmental influences appear to contribute to its development (Kolahchi et al.). Sex differences in adult cognitive function may have an underlying basis in both organizational effects, which originate during the early period of neuronal development, and activational effects, where sex hormones affect brain function throughout adulthood (Li and Singh). Specifically, the roles of progesterone, estrogens, and androgens, which are sex hormones, are recognized in the context of aging and AD development (Bianco et al.). Since the decrease in steroid hormones in men is less compared to women who experience post-menopausal estrogen depletion through aging, these differences could further explain the higher susceptibility of women to AD (Scheyer et al.).

In terms of sex differences in the brain’s structure and function associated with music processing, continuous electroencephalogram (EEG) and Event-Related Potentials (ERP) have revealed that music-syntactic processing is bilateral in females, whereas it is lateralized to right hemispheric predominance in males (Koelsch et al.). Furthermore, females demonstrate enhanced language and verbal learning (Kramer et al.) compared to males, likely due to the bilateral nature of language processing in female brains (Koelsch et al.). Hence, the processing of musical information is also found to be impacted by sex differences, in addition to linguistic

regions (Koelsch et al.). Data obtained through electrophysiological measures have shown females having significantly increased sensitivity to aversive and unpleasant music, including ‘heavy metal’ (Nater et al.). Potential sex differences in the perception and processing of music are evident through these studies; however, sex differences in the effects of MT, and specifically in older adults with cognitive impairment, remain poorly understood.

Methods

Measures and Assessments

The publicly available dataset obtained from the Mendeley Data Repository consisted of results from an investigation on the *Effects of One-to-One Music Therapy in Older Adults With Cognitive Impairment* conducted by Mangiacotti et al.. Based on this original dataset, analyses of the sex differences in the effectiveness of MT were performed. In the original dataset, the participants consisted of 42 older adults with mild to moderate cognitive decline living in care homes, with a mean age of approximately 86 years (Mangiacotti et al.). Of the 42 older adults, 35 were female and 7 were male (Mangiacotti et al.). Through a randomized controlled trial, participants were randomly assigned to either a 4-month one-to-one MT intervention group or a matched storytelling (ST) control group (Mangiacotti et al.). 23 older adults were assigned to the MT group, of which 20 were female and 3 were male (Mangiacotti et al.). Various cognitive and mood/behavioral tests were conducted both pre- and post-intervention (Mangiacotti et al.). Results suggested improvements in cognitive, behavioral, and physiological aspects in the MT group compared to the ST group (Mangiacotti et al.).

The primary cognitive measure was the Music Cognitive Test (MCT) (Mangiacotti et al.). The test measures cognitive functions that are highly sensitive to the specific skills that are intended to improve through music-based interventions, such as executive function and attention (Mangiacotti et al.). The Montreal Cognitive Assessment (MOCA) (Nasreddine et al.), which screens for neurocognitive impairment, was introduced as one of the secondary cognitive measures (Mangiacotti et al.). Regarding mood and behavioral variables, the primary behavioral measure utilized in the study was the Cornell Scale for Depression in Dementia (CSDD) (Alexopoulos et al.). The CSDD considers both participant and caregiver perspectives through administering questionnaires to both in identifying symptoms of major depression in the cognitively impaired individual (Mangiacotti et al.). One of the secondary behavioral measures was the Satisfaction With Life Scale (SWLS) (Diener et al.), a self-reported measure widely used to assess overall life satisfaction, which is highly sensitive to changes throughout treatment interventions (Pavot and Diener).

Statistics

All statistical analyses were conducted using R programming. Wilcoxon rank-sum tests were performed on each measured test variable comparing the pre-MT intervention and post-MT

intervention between sexes. Results with p-values of less than 0.05 are considered statistically significant.

Results

MCT-Based Analysis of Cognitive Effects of Music Therapy

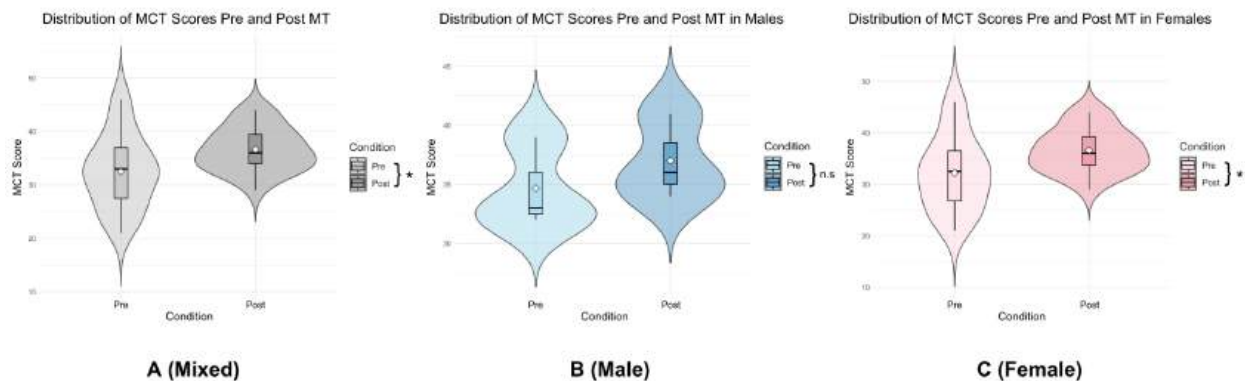


Figure 1: Distribution of Music Cognitive Test (MCT) Scores Pre- and Post-Music Therapy (MT) in Mixed Sexes, Male, and Female Groups. Figure 1A considers the entire group, combining both sexes, while Figure 1B and Figure 1C segregate the group by sex into males and females, respectively. Boxplots in the violin plot display medians and interquartile ranges, while diamonds represent the mean values. Asterisks (*) indicate significant differences (p-value < 0.05), while 'n.s.' refers to non-significance.

The MCT assesses cognitive functions using a score ranging from 0 to 52 points, with scores of 45 and above indicating cognitive normality (Mangiacotti et al.).

To investigate the effects of MT on the entire group (n = 23), I measured the significance of the differences in MCT scores between pre- and post-MT as a group. MCT scores in post-MT exhibited significantly higher values than pre-MT, indicating a significant improvement of cognitive functions upon MT (Wilcoxon rank-sum test; p-value = 0.01) (Figure 1A).

Next, to investigate whether there are sex differences in the improvements of the MCT scores, I separated the entire group by sex into male (n = 3) (Figure 1B) and female (n = 20) (Figure 1C) categories. A significantly higher improvement was observed in females compared to males. When analyzing males from the group solely, post-MT scores did not show a significantly higher value than the pre-MT scores (Wilcoxon rank-sum test; p-value = 0.38) (Figure 1B). On the other hand, the females in the group revealed significant differences and improvements between pre- and post-MT MCT scores (Wilcoxon rank-sum test; p-value = 0.02) (Figure 1C).

The results suggest a significant improvement in MCT scores as a whole group as well as in females, while there is no significant improvement for males between pre- and post-MT. These analyses reveal sex differences in the effectiveness of MT in the primary cognitive measure of MCT.

MOCA-Based Analysis of Cognitive Effects of Music Therapy

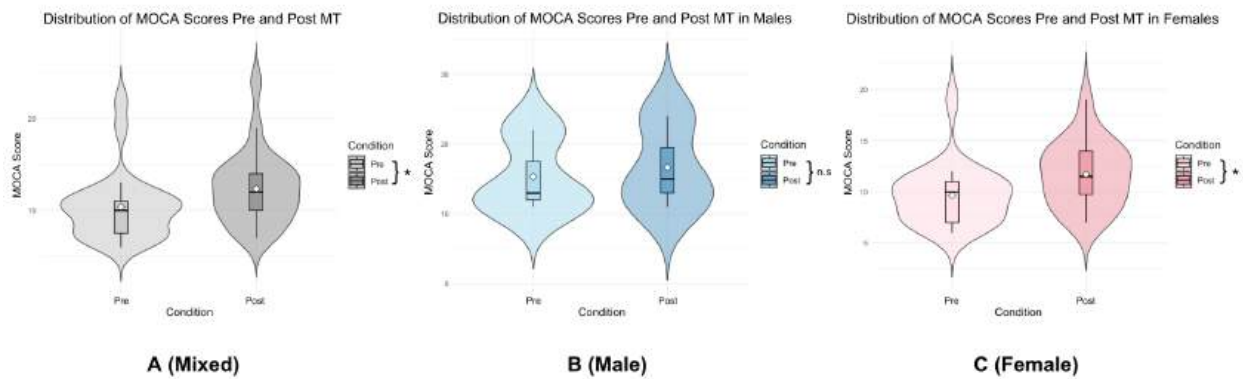


Figure 2: Distribution of Montreal Cognitive Assessment (MOCA) Scores Pre- and Post-Music Therapy (MT) in Mixed Sexes, Male, and Female Groups. Figure 2A considers the entire group, combining both sexes, while Figure 2B and Figure 2C segregate the group by sex into males and females, respectively. Boxplots in the violin plot display medians and interquartile ranges, while diamonds represent the mean values. Asterisks (*) indicate significant differences ($p\text{-value} < 0.05$), while 'n.s' refers to non-significance.

Measuring neurocognitive abilities such as executive and visuospatial functions, the MOCA score ranges from 0 to 30 points, with scores of 26 and above indicating cognitive normality (Nasreddine et al.).

Firstly, as an entire group ($n = 23$), I investigated the significance of the differences in MOCA scores between pre- and post-MT. Compared with pre-MT MOCA scores, post-MT scores revealed significantly higher values, demonstrating a significant improvement of cognitive functions (Wilcoxon rank-sum test; $p\text{-value} = 0.04$) (Figure 2A).

Secondly, I separated the entire group by sex into male ($n = 3$) (Figure 2B) and female ($n = 20$) (Figure 2C) categories to analyze whether there are sex differences in the changes of the MOCA scores. In females, a significantly higher improvement was observed compared to males. In the male group, post-MT scores did not show a significantly higher value than the pre-MT scores (Wilcoxon rank-sum test; $p\text{-value} = 0.82$) (Figure 2B). In contrast, when the female group was analyzed, significant changes and improvements were observed between pre- and post-MT MOCA scores (Wilcoxon rank-sum test; $p\text{-value} = 0.03$) (Figure 2C).

Hence, similarly to MCT scores, the findings indicate a significant improvement in MOCA scores as a whole group and in females, while no significant improvement is observed for males between the pre- and post-MT periods. Thus, sex differences can be seen in the effectiveness of MT in the cognitive assessment of MOCA.

CSDD-Based Analysis of Behavioral Effects of Music Therapy

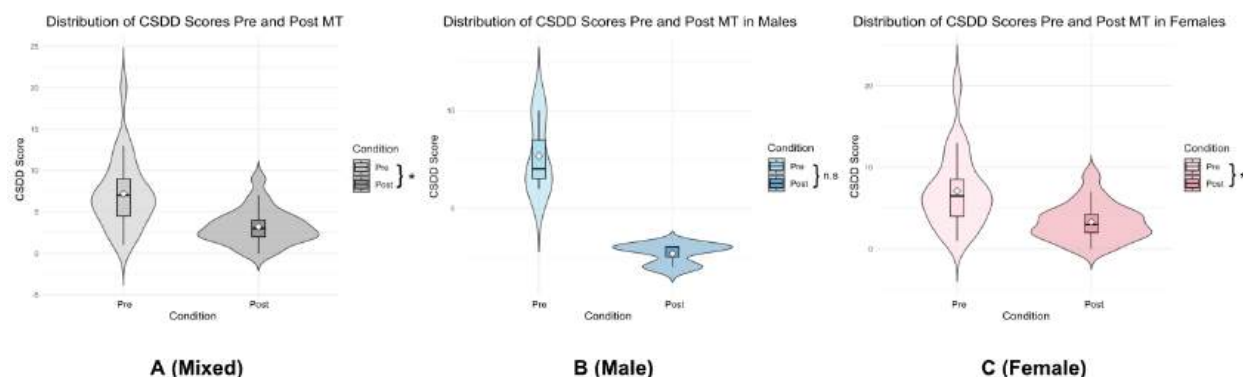


Figure 3: Distribution of Cornell Scale for Depression in Dementia (CSDD) Scores Pre- and Post-Music Therapy (MT) in Mixed Sexes, Male, and Female Groups. Figure 3A considers the entire group, combining both sexes, while Figure 3B and Figure 3C segregate the group by sex into males and females, respectively. Boxplots in the violin plot display medians and interquartile ranges, while diamonds represent the mean values. Asterisks (*) indicate significant differences (p -value < 0.05), while ‘n.s.’ refers to non-significance.

The CSDD evaluates signs of major depression through tests carried out on both the cognitively impaired individual and their care staff (Alexopoulos et al.). Consisting of 19 items, the scale uses a 3-point rating system, with the sum of all items producing the total score (Alexopoulos et al.). A score of 10 or higher suggests a probable major depressive episode, while 18 or higher indicates a definite major depressive episode (Alexopoulos et al.).

The significance of the differences in CSDD scores between the pre- and post-MT groups was investigated as a whole ($n = 23$). A significantly lower value of CSDD scores in post-MT was observed when compared with pre-MT, indicating a significant improvement through MT in this behavioral category (Wilcoxon rank-sum test; p -value = 3.03×10^{-4}) (Figure 3A).

To measure sex differences in the improvement of CSDD scores, I separated the entire group by sex into male ($n = 3$) (Figure 3B) and female ($n = 20$) (Figure 3C) subgroups. The results revealed a significantly higher improvement in females compared to males. Specifically, the male group had no significant difference, and post-MT scores were not significantly lower than the pre-MT scores (Wilcoxon rank-sum test; p -value = 0.08) (Figure 3B). However, females showed a significant decrease and improvement in their post-MT CSDD scores (Wilcoxon rank-sum test; p -value = 2.31×10^{-3}) (Figure 3C).

In parallel with MCT and MOCA scores, there are significant improvements in CSDD scores as a whole group and in females; however, no significant improvements are evident for males between the pre- and post-MT periods. Thus, findings suggest sex differences in the effectiveness of MT in the primary behavioral measure of CSDD.

SWLS-Based Analysis of Behavioral Effects of Music Therapy

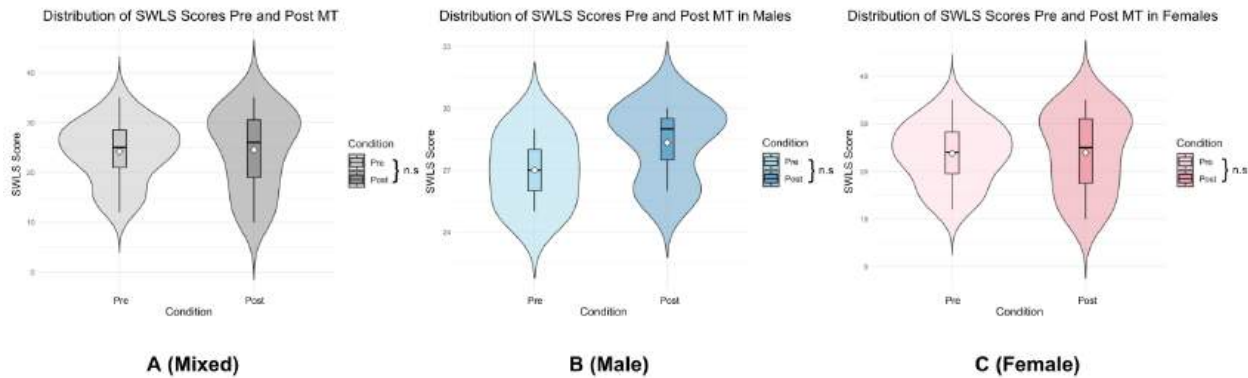


Figure 4: Distribution of Satisfaction With Life Scale (SWLS) Scores Pre- and Post-Music Therapy (MT) in Mixed Sexes, Male, and Female Groups. Figure 4A considers the entire group, combining both sexes, while Figure 4B and Figure 4C segregate the group by sex into males and females, respectively. Boxplots in the violin plot display medians and interquartile ranges, while diamonds represent the mean values. Asterisks (*) indicate significant differences (p -value < 0.05), while 'n.s' refers to non-significance.

Overall life satisfaction is assessed through the self-reported SWLS, which consists of five items, each rated on a 7-point scale from "strongly disagree" to "strongly agree" (López-Ortega et al.).

To investigate the effects of MT, I first evaluated the significance of the changes in SWLS scores between the pre- and post-MT periods for the entire group ($n = 23$). Results indicated that the SWLS scores obtained post-MT were not significantly higher than pre-MT scores, not revealing a significant improvement in life satisfaction following MT (Wilcoxon rank-sum test; p -value = 0.64) (Figure 4A).

Subsequently, to assess potential sex differences in SWLS score improvements, I categorized the group by sex into male ($n = 3$) (Figure 4B) and female ($n = 20$) (Figure 4C) subgroups. In both female and male categories, significant improvements were not observed. Regarding the male group, post-MT scores were not significantly higher than the pre-MT scores (Wilcoxon rank-sum test; p -value = 0.51) (Figure 4B), while females did not exhibit significant improvements in their post-MT SWLS scores as well (Wilcoxon rank-sum test; p -value = 0.83) (Figure 4C).

In contrast to the three tests above, no significant improvements in SWLS scores were identified as a group, in females, or in males. Hence, the behavioral scale of SWLS does not demonstrate sex differences in the effectiveness of MT.

Discussion

The objective of this study was to investigate the potential sex differences in the effectiveness of MT through various cognitive and behavioral measures. Extracting two tests each for cognitive and behavioral categories—MCT, MOCA, CSDD, and SWLS—the results suggested that the first three tests exhibited the same pattern, whereas SWLS was inconsistent with them. The two cognitive tests—MCT and MOCA—as well as the primary behavioral measure, CSDD, showed a significant improvement in scores between the pre- and post-MT

periods when examined as a whole group and when analyzed separately for females. However, the male group did not indicate a significant improvement. Therefore, sex differences in the effectiveness of MT are evident throughout these three tests. In the SWLS, a secondary behavioral measure, results did not demonstrate a significant improvement in scores between pre- and post-MT in all three categories: whole group, females, and males. This observation could be due to the vagueness and broad nature of the SWLS scales (Mangiacotti et al.). Subjective criteria such as ‘the conditions of my life are excellent’ or ‘I am satisfied with my life’ are overly generalized and might not have been adequately sensitive to subtle changes influenced by a few months of MT in these cognitively impaired individuals. Conversely, it might indicate that the MT interventions had limited effectiveness in this particular category (Mangiacotti et al.).

As the role of sex hormones is known to impact aging and AD development (Bianco et al.), and the significant decrease in these hormones further contributes to women being more susceptible to AD as they age (Scheyer et al.), the role of biological sex differences in neurodegenerative diseases is evident in older adults. Thus, investigating sex differences in cognitive function and sex-specific mechanisms is crucial for developing personalized, sex-specific treatments, as well as for a more effective diagnosis (Li and Singh; Kolahchi et al.). Koelsch et al. highlight that music-syntactic processing is bilateral in females. At the same time, it is focused on the right hemisphere in males, and potential sex differences in the perception and processing of music have also been identified. Despite studies revolving around this topic having been conducted, the sex differences in the effects of MT, and particularly among older adults with cognitive impairment, are still not well understood.

The original article by Mangiacotti et al. investigated the effects of MT versus ST on cognitive and behavioral domains in older adults with cognitive impairment. Building on this original dataset and focusing on the MT group, the sex differences in improvements on cognitive and behavioral tests were analyzed. In the original dataset, the MT group showed significant improvements in general cognitive functions, as measured by the MCT and MOCA, compared to the ST group, which did not (Mangiacotti et al.). Additionally, there were significant differences between MT and ST for CSDD; however, SWLS showed stability across the intervention for both groups (Mangiacotti et al.). The findings align in pattern with the current investigation. Although the original study did not conduct sex-specific analyses, tests that originally exhibited significant improvements in the MT group—MCT, MOCA, and CSDD—revealed a clear pattern in the current investigation: a significant improvement in females but not in males. Therefore, this research made evident the sex differences that were present in the original study.

Since two-thirds of Americans who are diagnosed with AD are women (Kolahchi et al.), the sample size in this study consisted predominantly of females. Among the group, which included 23 older adults with cognitive impairment, 20 were female and only 3 were male. Considering that the majority of the findings revealed a significant difference in females but not in males, this could be attributed to the limited number of male participants, which made the sample size unrepresentative of the population. It can be speculated that with a more balanced

sex distribution, outcomes may have differed, and significant findings might have emerged for males as well. Regarding CSDD scores, the average initial score of the group was approximately 7.17, which is outside the cutoff zone representing no diagnosis of depression. Hence, this suggests that the decrease in CSDD scores may not indicate a recovery in the level of depression but instead an improvement within a range already demonstrating non-depression (Mangiacotti et al.).

Future studies should research a larger and more representative sample of sexes to enhance the validity of their findings. Since data collection was performed solely through questionnaires and survey results, the findings may have been subjective and could have been influenced by misinterpretation. Further research can be conducted using scientific technologies, such as MRI scans and measuring brain activity, to reduce subjectivity and enhance the validity of the results.

In conclusion, this investigation contributes to the findings of sex differences in the effectiveness of MT in older adults with cognitive decline. The findings highlight the importance of considering sex differences in MT, as well as suggesting the future potential for sex-specific tailored MT approaches that can most effectively use music as a non-invasive treatment in cognitively impaired individuals. Ultimately, with MT's promising therapeutic potential, these individualized methods can improve the overall health and well-being of older adults as life expectancy continues to rise.

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AI in Running Injury Prediction & Prevention Final Paper By Aidan Sharp

Abstract

Analyzing data about running training versus injuries is important for several reasons, primarily benefiting athletes, coaches, and sports scientists. For example, understanding the specific thresholds or rapid increases in training volume that lead to common injuries like shin splints or IT band syndrome can help coaches design progressive training plans that minimize risk while still maximizing performance gains. Ultimately, this data analysis contributes to a more scientific and evidence-based approach to running, moving beyond traditional theories to provide actionable insights for injury prevention. Our results proved that out of the models we used the Random Forest Regression had the highest accuracy (99%) while the MLP Classifier had the lowest accuracy (67%). We concluded that every model given enough training data proved to be quite accurate so the most important part of machine learning is feeding the algorithm enough useful data.

Introduction

The high incidence of running-related injuries—affecting up to 79% of runners annually—presents a significant challenge to consistent training and athletic longevity. Traditional injury prevention research has predominantly focused on external metrics such as training volume (mileage), biomechanical variables (e.g., cadence and ground contact time), and strength imbalances. While these factors are critical, they often overlook the runner's immediate, subjective, and physiological response to the imposed training load, which is arguably the most crucial indicator of overall stress and susceptibility to breakdown.

I think a more holistic and predictive model for injury risk must integrate internal training load metrics derived from the athlete's self-reported experiences. This paper investigates the utility of easily accessible subjective measures—specifically, Perceived Exertion (RPE), Perceived Effort, and Recovery Time—as core predictive features for musculoskeletal injury in runners.

The concept of training load distinguishes between the External Load (the work performed, e.g., speed and distance) and the Internal Load (the physiological and psychological stress resulting from the work). Metrics like the Session-RPE (sRPE), which multiplies the RPE score (a 1-10 scale rating the intensity of a workout) by the duration of the session, have proven valuable in team sports for quantifying internal stress. Crucially, the Acute-to-Chronic Workload Ratio (ACWR*, which compares a runner's training volume over the last week (acute) to their average volume over the last four weeks (chronic), has emerged as a powerful tool. However, most ACWR models rely solely on *external* load (e.g., total distance).

Our research seeks to bridge this gap by applying machine learning to a dataset rich in these subjective metrics. We hypothesize that incorporating self-reported data on Perceived Effort (a related but distinct cognitive assessment of the difficulty), Perceived Exertion (RPE), and the required Recovery Time into predictive models will significantly enhance the accuracy

of individual injury risk stratification compared to models relying on external load alone. By focusing on these readily available and non-invasive subjective metrics, this study aims to develop a practical, scalable, and highly personalized system for proactive injury prevention.

1. "Predicting Running Injuries with Classification Machine Learning Models"

This paper directly addresses the core of my project: can I predict injuries using a dataset and machine learning? The authors use classification models like Logistic Regression and Random Forest on a dataset of runners' workouts and injuries. I found their emphasis on working with an imbalanced dataset (many more healthy days than injured days) particularly relevant, as they used techniques like over and under-sampling to solve this. The study concluded that a weighted logistic regression model was most effective, which tells me I need to be careful about choosing the right algorithm for the specific characteristics of my own dataset.

2. "A machine learning approach to identify risk factors for running-related injuries: study protocol for a prospective longitudinal cohort trial"

This is a study protocol, which is useful because it outlines the methodology for a long-term research project. The authors plan to use machine learning to analyze a wide range of data from runners, including biomechanical parameters (like gait), physiological data, and training load. Their goal is to move beyond simple training load analysis and identify complex, individual-specific risk factors. This paper is valuable to me because it discusses the need for a multifactorial approach and highlights the advantage of machine learning in uncovering subtle patterns in complex datasets that might be missed by traditional statistical methods.

3. "Injury Prediction in Competitive Runners With Machine Learning"

This paper, published in the *International Journal of Sports Physiology and Performance*, uses machine learning to predict injuries in competitive runners based on detailed training logs. The researchers used the Extreme Gradient Boosting (XGBoost) algorithm, a powerful machine learning model known for its high performance. They found their model was reasonably accurate, especially when analyzing training load data from the days immediately before an injury. This study helps me understand the importance of using real-time data and a granular, micro-level analysis for effective injury prediction.

Methods

This dataset, titled "Injury Prediction for Competitive Runners," is a rich, longitudinal, time-series resource designed to facilitate the use of machine learning in predicting running-related musculoskeletal injuries. Sourced from the detailed training logs of 74 high-level Dutch middle- and long-distance runners over a seven-year span (2012–2019), it provides a unique window into the training stress and recovery cycles of elite endurance athletes.

The data is structured primarily at the weekly level, where each observation summarizes a runner's training activities for a given week. It features an extensive collection of nearly 70 variables categorized to capture the complexity of training load:

Objective External Load: Quantifiable metrics like total distance run, the number of training sessions, and the distance covered in specific high-intensity heart rate or speed zones.

Subjective Internal Load: Crucial self-reported measures, including the number of "tough" sessions (based on high Perceived Exertion or RPE), the runner's average and maximum perceived training success, and the subjective time required for recovery.

Derived Temporal Features: Metrics that encode the relationship between training history and present load, such as the Acute-to-Chronic Workload Ratio (ACWR), which are calculated by comparing current weekly volume to a rolling average.

The machine learning objective is a supervised classification task, with the binary target variable indicating whether a runner sustained an injury during that week or within a short, subsequent prediction window. Although the dataset is extensive, with over 42,000 observations, it exhibits a significant class imbalance, which is inherent to injury prediction problems since injury occurrences (the positive class) are rare relative to healthy training weeks (the negative class). This comprehensive dataset allows researchers to test whether integrating non-invasive, subjective measures offers superior predictive power compared to models based solely on objective metrics.

The models used for analysis included:

Decision Tree: A foundational, non-linear model that partitions the data based on single feature values, creating an interpretable, tree-like structure to arrive at an injury prediction.

Random Forest: An ensemble learning method built upon multiple decision trees. By training numerous trees on random subsets of the data and features and aggregating their predictions (voting), it significantly reduces the risk of overfitting and often achieves higher accuracy than a single decision tree.

MLP Classifier (Multi-Layer Perceptron): A type of basic feed-forward neural network. This model is highly effective at capturing complex, non-linear relationships within the data, treating the features as weighted inputs across multiple layers to learn intricate patterns indicative of injury risk.

Logistic Regression: A fundamental linear classification model. Despite its simplicity, it is crucial for establishing a baseline by calculating the probability of injury through a linear combination of the input features, providing interpretability regarding the impact of individual metrics (like ACWR or RPE) on risk.

K-Nearest Neighbors (KNN): A non-parametric, instance-based learning algorithm. It classifies a new training week based on the majority class (injured or non-injured) of its k closest neighbors in the feature space, making it a valuable tool for identifying localized risk clusters in the athlete's training profile.

Results

The results presented highlight a common and critical challenge in machine learning applications for injury prediction: the deceptive nature of high accuracy in severely imbalanced datasets.

Here is an analysis of the provided model accuracies in the context of the running injury dataset:

Model	Reported Accuracy	Total Injured Cases	Total Not Injured Cases
Decision Tree	98.7%	166	12,664
Random Forest	99%	166	12,664
MLP Classifier	67%	(N/A)	(N/A)
Logistic Regression	98.6%	(N/A)	(N/A)
K-Nearest Neighbors	98.6%	(N/A)	(N/A)

Export to Sheets

Interpretation of Results

High Accuracy is Misleading (for Random Forest, Decision Tree, Logistic Regression, and KNN):

The dataset is severely imbalanced: out of $12,664 + 166 = 12,830$ samples, the majority class (Not Injured) accounts for $12,664/12,830$

$\approx 98.7\%$.

A "dummy" model that predicts "Not Injured" for every single case would achieve an accuracy of 98.7%.

Therefore, the reported accuracies of 98.6% to 99% for the Random Forest, Decision Tree, Logistic Regression, and K-Nearest Neighbors models indicate that they are likely doing very little more than simply predicting the majority class. They are excellent at predicting "Not Injured," but are almost certainly failing to correctly identify the rare, critical "Injured" cases. This means their practical utility for proactive injury prediction is extremely low, despite the high accuracy score.

The MLP Classifier (67% Accuracy):

The MLP Classifier's lower accuracy of 67% is noteworthy. This suggests that this model is attempting to learn the complex patterns of the minority class (Injured) and is, in the process, making more errors on the majority class.

While the overall accuracy is lower, the MLP might be the better model because it is potentially achieving a higher Recall (Sensitivity) and/or F1-Score for the Injured class. A model

with 67% accuracy but a high recall for the positive class is more useful for clinical prediction than a model with 99% accuracy that misses all the injuries.

While accuracy is a commonly reported metric in machine learning, relying on it alone can be misleading, particularly in the context of injury prediction. This is because the dataset is often imbalanced—there are typically far fewer injury cases compared to non-injury cases. In such situations, a model can achieve very high accuracy simply by predicting the majority class (i.e., “no injury”) most of the time, without actually learning meaningful patterns that identify athletes at risk.

Recall (Sensitivity) for the Injured Class: How many of the actual injuries did the model correctly identify? (This is the most critical metric for proactive prevention.)

Precision for the Injured Class: Of all the cases the model predicted as "Injured," how many were actually injured? (This relates to the number of unnecessary warnings/false alarms.)

F1-Score: The harmonic mean of Precision and Recall, which provides a single, balanced score for imbalanced data.

Area Under the ROC Curve (AUC): Measures the model's ability to distinguish between the two classes regardless of the classification threshold.

The low inherent base rate of injury necessitates a shift from optimizing for overall accuracy to optimizing for Recall and F1-Score on the minority class.

Because the base rate of injury is inherently low, focusing solely on overall accuracy can create a false sense of performance. Therefore, the evaluation should prioritize recall and F1-score on the injury (minority) class, ensuring that models are not just accurate in aggregate, but also effective at detecting the relatively rare yet clinically critical injury cases. This shift in focus aligns predictive modeling with the real-world objective: preventing injuries before they occur.

Discussion

While our results regarding each model appeared to be quite promising, due to the fact that the actual injured to not injured ratio was nearly 100%, it's hard to argue against the fact that our models with 98-99% accuracy likely took the safe route of predicting no-injury every time, making them not extremely useful for actually determining injury, because the whole point is to detect injuries when they do occur, rather than never detect injuries. While our MLP Classifier did quite poorly relative to the other models (67% accuracy) it may be the most effective because it actually learned from the training data rather than just settling with an easy 98% accuracy by always ruling out the possibility of injury. The next steps I would take with my research are to use the same models again but use them on more selective data where the actual data has a better ratio of injured to non-injured athletes, maybe 70-30 or so. This would force the models to actually learn how RPE vs recovery time affects an athlete and would be able to have better judgement.

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Recognizing Leonardo da Vinci and His Contributions to the Axial Skeleton

By Audrey Lee

Introduction

The *Mona Lisa* and *The Last Supper* are among the top ten most visited art pieces in the world, massing millions of people each year (Brown, 2019). Both created from the same artist, Leonardo da Vinci is often associated for his contributions in art during the 15th-16th centuries. Although it is important to acknowledge his pieces of art, there has been a lack of recognition in his greater accomplishments through varying fields with an intersection of art, science, and innovation. In fact, it is stated that 76% of the world population knows him just for his artistic abilities (YouGov). Among his many contributions include an advancement in human anatomy, containing detailed observations of the axial skeleton that include the skull, vertebral column and the thoracic cage. At a time when anatomical study was constrained by social and religious barriers, da Vinci's works went beyond ambition to inform a scientific understanding that was centuries ahead of its time. His dissections, sketches, and notes laid the groundwork for modern anatomical knowledge structurally in the 21st century.

Despite his significant influence, Leonardo's contributions to anatomy, including his axial skeleton studies, are often overshadowed by his artistic masterpieces. Mohammad Bayat, a Ph.D. Senior Research Scientist in the field of Biology and Anatomy, criticizes the fact that there is much less recognition in da Vinci's accomplishments within science compared to the works of his art (Bayat M., 2020). This is why I crafted a question that I sought to answer "How accurate are Leonardo da Vinci's depiction of the axial skeleton in the Anatomical Manuscript A compared to anatomically correct models in the 21st century?" The purpose of my research is to explore to the extent of Leonardo's anatomical insights and calculating the accuracies between his works from the 16th century to the 21st, emphasizing why his contributions remain vital to both the history of science and modern anatomical studies. For my analysis, I will be conducting a content analysis evaluation by extensively researching peer reviewed works pertaining to his significant findings, both accurate and inaccurate, in the axial skeleton as well as collecting quantitative data by initiating a structural similarity index analysis to examine the proximate accuracies and differences in da Vinci's works in the *Anatomical Manuscript A* to the 21st century. By acknowledging Leonardo's legacy, we not only honor his achievements but also recognize the enduring relevance of his approaches to understanding human anatomy.

Gap in the Research

Pre-existing research of this topic lacks the discussion with comprehensive comparison between Leonardo da Vinci's axial skeleton studies and contemporary anatomical knowledge. Most existing research highlights da Vinci's anatomical achievements broadly, such as his dissection practices, muscular studies, or artistic precision (Amsen, E. 2019). Rather than focusing on the axial skeleton, numerous research has focused on da Vinci's contributions to the nervous system and the current knowledge, investigating the anterior and middle meningeal

artery, the posterior cranial fossae, and most importantly the spinal cord (Bowen, Gonzales, Iwanaga, Fisahn, Loukas, Oskouian, R. J., & Tubbs, 2017). After reviewing numerous studies pertaining to the specific scientific contributions da Vinci had with the nervous system, it is clear that there is a lack of attention with the axial skeleton. Recognizing the axial skeleton is crucial to contributions of science, as it plays a critical role in both structural support and protects the central nervous system. Another gap in my research was the lack of mention of da Vinci as well as the time period of research with the initial contributions he had for the axial skeleton. Many mentions of initial research with the axial skeleton pertaining specifically to the dates from the 1800s throughout the 2000s, with no mention to discoveries before the time period(). By digging further into this research, I can explore how da Vinci's depiction of its biochemical functions compare to the modern interpretations, thus recognizing the importance of this specific contribution. While scholars recognize Leonardo's influence in artistic and anatomical contributions, the full impact on the axial skeleton studies and their lasting significance in science and medicine remains unexplored. By researching this topic, I will be able to highlight da Vinci's role in advancing the understanding of the axial skeleton and making a case for the continued relevance of historical anatomical studies in modern science.

Search Strategies

Sources were located via scrutinizing various databases with limited extent of peer reviewed works to ensure credibility. Keywords while researching were: Leonardo da Vinci, axial skeleton, Anatomical Manuscript A, Structural Similarity Index.

Anatomical Manuscript A

Leonardo da Vinci's anatomical manuscripts are a collection of detailed drawings, notes, and observations he created during his empirical studies of the human body during his dissections in the St Jerome (Pevsner, 2005). These manuscripts include the famous *Codex Atlanticus* and *Windsor Anatomical Manuscripts* that documented his groundbreaking efforts to understand human anatomy through direct dissection and observation. These manuscripts not only reflect his contribution to artistic mastery and knowledge but also emphasized his scientific achievements, as he approached anatomy with a level of precision and insight that was unique and unparalleled for his time. The specific manuscript I will be focusing on is his *Anatomical Manuscript A* 1510-11, which includes eighteen pages of his works that focused on the study of anatomy from up to thirty possible dissections he conducted (Stephan, 2010). The *Anatomical Manuscript A* specifically hones in on the specific pieces of muscle and bone diagrams da Vinci catalogued, which include the parts of the axial skeleton (the cranium, torso, and vertebral column). Researchers specifically broke down the way he sketched out his diagrams, as he used the art of omission to disassemble the spin into individual parts to graphically illustrate the structure. By doing so, he would enlarge certain bones disproportionately to emphasize the particular functionality, as Alessandro Nova, an Italian art historian, quotes, "Through this tersest way of

drawing from various perspectives, one provides full and true knowledge of them” (Hinterkeuser, 2019).

It is also important to note that da Vinci had no references at the time to approximate these graphic visualizations of the inner workings of the human body. Researchers have already compared the knowledge Leonardo gathered in the *Anatomical Manuscript A* accrediting the accuracies of his works for the being of the time, thus making his works even more impressive when considering that variable (Heydenreich, 2024).

Axial Skeleton

The bones in a human body are divided into two main parts: the appendicular skeleton and the axial skeleton. According to the National Cancer Institute, the axial skeleton is a fundamental structural base of the body that makes up 80 bones of the body, including the cranium, vertebral column, and thoracic cage. It serves to support and protect the heart, lungs, and central nervous system that also makes up the brain and spinal cord. According to Kara Rogers, a senior editor of biomedical sciences at Encyclopaedia Britannica, the axial skeleton acts as a base and was one of the first of the body parts to evolve, that supports the soft parts of the human body such as the nervous system, digestive system, respiratory system, cardiovascular system, and voluntary muscles of the muscle system.

More specifically, the cranium has a set of two bones that include eight cranial bones that make up the sections of the skull and support the brain and fourteen facial bones that make up the face of the skull that form an entrance to the body. The eight cranial bones include: two parietal bones, two temporal bones, one frontal bone, one occipital bone, one ethmoid bone, and one sphenoid bone. The fourteen facial bones include two maxillary bones, two zygomatic bones, one mandible bone, two nasal bones, two palatine bones, two nasal concha bones, and two lacrimal bones (Williams, Alkhatib, Serra, 2022). For the purpose of feasibility in my research, the section I will be focusing on in the skull are the cranial bones.

The thoracic cage acts as a function to protect the heart, lungs, and other organs that lay in the chest region of the body that supports muscles involved with respiration and arm movement. There are a total of 37 bones which make up the cage that include one sternum, 12 thoracic vertebrae and an average of 24 ribs. The sternum is an elongated structure that acts as an anchor for the anterior of the thoracic cage that attaches itself to the 12 thoracic vertebrae. Each rib is a curved, flattened bone that contributes to the wall of the thorax that mostly attach to the anterior of the costal cartilage to the sternum. For the feasibility of my research, I will only be analyzing the pairs of ribs and classify them based on their sections. The ribs in the thoracic cage are classified into three different types, with ribs 1-7 classified as true ribs (vertebrosternal ribs), ribs 8-12 classified as false ribs (vertebrochondral ribs), and the last two false ribs being named floating ribs (vertebral ribs) (Bronson, et. Al, 2019).

The last part of the axial skeleton I will be discussing is the vertebral column, which consists of 33 vertebrae that are separated by disks and are classified into 5 distinct areas (Campellone, 2024). First is the cervical spine that makes up the first seven vertebrae, making up

the region of the neck, allowing humans the ability to hold their neck up right and make twisting motions (2022). The thoracic spine is the next section, consisting of 12 vertebrae numbers from T1 to T12, each corresponding to the nerves connecting to the spinal cord and supplying movement and sensation to those areas of the body (Waxenbraum, 2023). The lumbar and sacrum both are made up of 5 vertebrae each, with the coccyx (tailbone) right underneath making up the lower spine and providing stability for the back and spinal column while also allowing for a point of attachment for muscles and ligaments. I will be using these categories of the vertebral column as a reference for my segmentations of analysis in my research.

Summary

It is clear that there is a lack of recognition in da Vinci's academically engrossing achievements, more specifically in his studies of the axial skeleton. These studies are central to the contribution of the human anatomy due to its structural and protective roles. Even though modern anatomy emphasizes its biochemical functions, it is important to understand the evolution of this knowledge and credit those such as da Vinci for the advancements in the field of knowledge. Throughout the 16th century, there were no available medical tools for da Vinci to use to analyze as he solely relied on empirical observations to create his anatomical sketches (Jones 2012). At this time as well, there was no previously released data on anatomical studies on the axial skeleton, thus meaning that da Vinci had no other sources to rely on, crediting his work to be solely his alone. Contemporary studies emphasize the importance of recognizing Leonardo's approach with combined arts and science to inform his anatomical observations. Despite the lack of recognition and focused research of his works with the axial skeleton, this creates an opportunity for further exploration, with this research allowing a greater understanding of da Vinci's relevance in science and medicine.

Methodology

Study Design

This study explores the correlation of da Vinci's findings in the Anatomical Manuscript A and the relevance of his works from 500 years ago pertaining to our current knowledge of the axial skeleton in the 21st century. The purpose of my research is to increase the awareness of da Vinci's contributions to our modern understanding of the world, not only for his most known field with art, but other fields of subjects such as mathematics, science, technology, and anatomy. Leonardo da Vinci is often associated with his accomplishments relating to the 'Mona Lisa' or 'The Last Supper' and there is a lack of recognition in much greater contributions he's made to our society. My specific focus will be examining his works contributing to anatomy, which can allow the scientific medical community to gain insight into the historical progression of anatomical science and the fundamentals that were worked on from centuries ago.

For my research design, I will conduct a two-part experiment that will allow me to collect both qualitative and quantitative data that will allow me to pinpoint the accuracies and faults in

his studies of the axial skeleton. This is important because the mixed-methods provides me with a more calculated response with quantitative data to further support my findings rather than just my empirical findings and research with qualitative data. The two methods I used to gather my data were: a content analysis of my focused research pages in the Anatomical Manuscript A being compared to diagrams and texts from the 21st century for qualitative data, as well as image processing techniques to calculate my quantitative data. Procedure

For my content analysis evaluation, I will be selecting primary sources from the scans of the Anatomical Manuscript A that contain the cranium, the torso, and the vertebral column. To obtain these scans, I will be using Martin Clayton's *Leonardo da Vinci The Mechanics of Man*, a book filled with collective research and scans published by the Royal Collection Enterprises, to obtain accurate translations of each of the pages. For the purpose of feasibility in my research, I will be doing an analysis focused on 3 specific sections of documented work in the manuscript, including the vertebral column, the cranium, and the torso. At the same time, I will also be using contemporary sources pertaining to the 21st century, such as extracting data from diagrams in modern anatomy textbooks, peer-reviewed articles, and medical databases to establish current knowledge of the axial skeleton through qualitative data. By analyzing the different materials, I will be able to conduct an empirical analysis by finding overlapping correlations and differences between the sources for qualitative data. To collect quantitative data, I will be running a structural similarity index simulation code through the platform, Python. This specific code analyzes individual pixels between two different images to understand and categorize an image as a whole under a specific label, otherwise, calculating the percent accuracy between the two. After segmenting the images into what I want to compare, I will be running each segment through an SSIM, using the 21st century diagram as a baseline while using the scans from the Anatomical Manuscript A to calculate relative accuracy. In order to ensure that I am correctly analyzing specifically the structure of the skeleton and no other factors (such as lighting, color, etc.) I will convert both medical diagrams and da Vinci's sketches through a line segment converter through the program, Saiwa. Saiwa is a program designed for finance, science, and engineering that allows for proper conversions between photos and segments, assisting me greatly through the conversion process. A specific program I used in Saiwa allowed me to convert the scans I will be using into line segments, highlighting the structure of the skeleton while also eliminating other outside disturbing factors that could hinder the SSIM scan, such as bad lighting, writing, degradation of paper, and any other factor that will distract from the structure alone (conversions shown from Figures 1-6). Saiwa's popular use among data scientists for structure analysis is what encouraged me to go through the process of the platform as well. In doing so, this research method will allow me to distinguish a certain correlation between our knowledge in the 21st century compared to the works of da Vinci from 500 years ago.

Variables

The first variables I had to determine were the specific pieces of da Vinci's works I will be analyzing. I decided to choose the Anatomical Manuscript A out of the 11 collections da Vinci had due to the fact it included the most information of his anatomical dissections that took place

in the University of Pavia, 1510-11. This would provide me with the most amount of information of his with the axial skeleton. I decided to focus on the axial skeleton due to the fact that da Vinci's sketches correlated the most to that part of the body and it was the strongest common occurrence I noted throughout the Anatomical Manuscript A. For the purpose of collecting my data, I will separate the axial skeleton into its three main components: the cranium, the torso, and the vertebral column. I will segment each section of the components into specific parts by using line segmentation, which will allow me to accurately identify the different sections of the component I will be studying when I run it through the structural similarity index.

Research Instruments

To collect quantitative data, I will be using multiple image processing codes that will allow me to calculate the differences of structural pixels there are between my comparisons from the Anatomical Manuscript A to the 21st century. The first instrument I will be implementing in my research is structural similarity index. This is a code on Python I can input with my two comparative images that will be able to isolate specific regions in an image. Structural similarity index image analysis can be used to isolate specific regions in an image, such as bones, muscles, or nerves in anatomical diagrams. This is especially useful when comparing Leonardo da Vinci's diagrams to modern anatomical representations of the axial skeleton, as it allows for a focused analysis of specific structures, commonly used by doctors and researchers. After conducting the image segmentation, I will be using a structural similarity index method (SSIM) to compare the extent of similarities there are between the two images through luminance, contrast, and structure. Even though this technique is often used in the film industry, SSIM is also commonly used for medical image SR research to find structural differences (Ahmad, Umirzakova, et. Al). Due to the fact that I am only observing the structural difference, I will be adjusting the luminance and contrast of the two images to equal measures, while keeping the arrangement of the image the same. After running a SSIM scan through each of the segmented images, I will be able to see an overall rate of accuracy for each section of the axial skeleton by taking the average of the measures, thus giving me a good source of quantitative information.

Table 1: *Mapping SSIM and VMAF Scores Subjective Ratings (Gozer, 2023).*

TABLE I
MAPPING SSIM TO MEAN OPINION SCORE SCALE

SSIM	MOS	Quality	Impairment
≥ 0.99	5	Excellent	Imperceptible
$[0.95, 0.99)$	4	Good	Perceptible but not annoying
$[0.88, 0.95)$	3	Fair	Slightly annoying
$[0.5, 0.88)$	2	Poor	Annoying
< 0.5	1	Bad	Very annoying

Results

The code for quantitative analysis was complete after a linearization of the used segments. The scans of the Anatomical Manuscript A as well as the medical resources provided was entered through a line segment converter that analyzes the structure of the shape and was then run through the SSIM code to measure the similarities. After measuring the codes, the results with the greatest number correlates to having the greatest similarity. For example, referring to the SSIM code table seen as Table 1, a score of ≥ 0.99 is the most accurate, with the quality of the two images being “excellent” and having the greatest similarity in structure. Any SSIM score of a < 0.5 or less is classified as “bad” with greatest impairment and near to none similarities in the structure.

The first scan I did was analyzing the cranium. I cleaned up the sketch from da Vinci’s Anatomical Manuscript A to remove all words and extra lining that could possibly hinder the results. In doing so, I am ensuring that the most accurates results would be produced from my analysis. Afterwards, the image was converted into line segmentation for analysis of the code through an SSIM program that was made to specifically analyze the structure of the images. As seen in Figure 1, the transformations of the sketch are shown, with the conversion of line segments ending up to be 150 lines with an execution of 0.05s. The model of the cranium I used was from Human Bio Media seen in Figure 2, which is the anatomically correct 21st century model (2022). I then converted the model into line segmentation through Saiwa, which resulted in 456 line segments with an execution time of 0.07s. By running the two converted line segment images through an SSIM scan, the eventual resultant was an SSIM score of 0.95 which is classified as “fair” through the SSIM scale on Table 1.

Figure 1: Conversion of the Cranium, Leonardo da Vinci

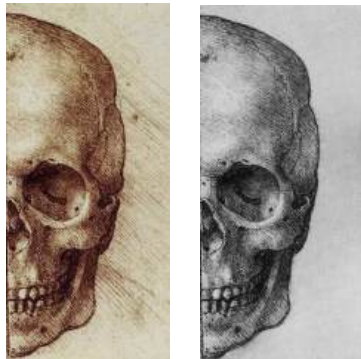


Figure 2: Conversion of the Cranium, Human Bio Media

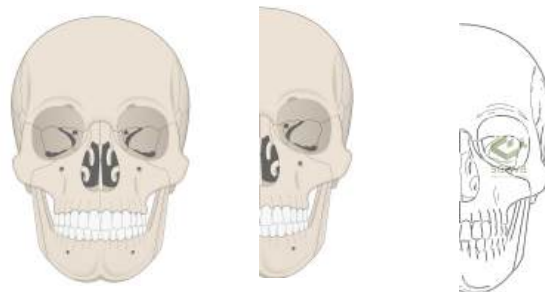




Table 2: SSIM Measurements of the Cranium

The second scan was pertaining to the vertebral column, which I then used an anatomically correct modern reference from the Cleveland Clinic of the spine structure as a reference to the comparison of Leonardo da Vinci's (2019). Conversion results included 68 line segments with an execution time of 0.02s from da Vinci's vertebral column (Figure 3) and 213 line segments from the anatomically correct diagram (Figure 4) with an execution time of 0.02s (results can be seen in Table 5). After running the SSIM program to measure the similarities with the structure, the coding resulted in a SSIM number of 0.977 (Table 3) which can be classified as "good" with an almost accurate structure to one another according to Table 1.

Figure 3: Conversion of the Vertebral Column, Leonardo da Vici



Figure 4: Conversion of the Vertebral Column, Cleveland Clinic



Table 3: SSIM Measurements of the Spine



The final analysis I did for the axial skeleton was the thoracic skeletal system, which was the most complicated structure that I was analyzing in the axial skeleton. I used another model from Cleveland Clinic of the thoracic structure as a reference which was compared against Leonardo da Vinci's sketch to the rib cage. Due to the fact of the system's difficult and complex structure, I adjusted the linearization to both lines and arcs, which would form a more accurate conversion. Da Vinci's sketch was successfully converted into 233 segments of arcs, and 1146 lines with a run time of 1.38s (Figure 5). The anatomically correct reference was converted into

178 arcs and 1231 lines with an execution time of 2.92s (Figure 6). After running the SSIM program, the resultant code was 0.152 (Table 4).

Figure 5: Conversion of Thoracic Skeletal System, Leonardo da Vinci

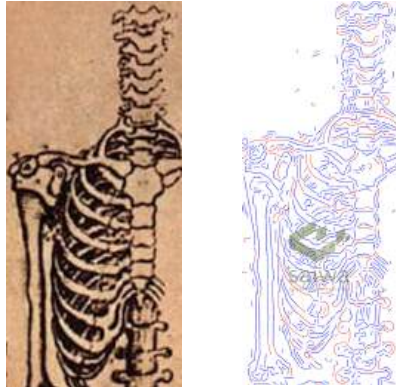


Figure 6: Conversion of Thoracic Skeletal System, Cleveland Clinic

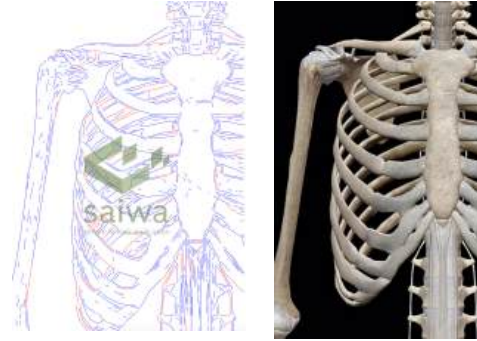


Table 5: SSIM Segmentation Results

Spinal cord data	Leonardo da Vinci's	Accurate
Number of line segments	68 !	213 !
Execution time	0.02s	0.02s
SSIM	0.977	0.977
MS-SSIM	0.0968	0.0968
Cranium data		
Number of line segments	150 !	456 !
Execution time	0.05s	0.07s
SSIM	0.95	0.95
MS-SSIM	0.9	0.9
Thoracic cage data		
Number of line segments	233 !	1146 !
Execution time	1.38s	2.92s
SSIM	0.152	0.152
MS-SSIM	0.011	0.011

Analysis

After examining the results, it can be concluded that the spinal cord is the most accurate out of all the systems in the axial skeleton. This is showcased through the near perfect score of the SSIM code as 0.977 as depicted in Table 5. This resultant was to be expected, as Leonardo da Vinci summed most of his findings to focus on the spinal cord specifically, with various attempts of finding the functions and resulting in different depictions of the spine (Springer, 2017). More specifically through the qualitative data I've gathered, da Vinci has made notable discoveries with the spinal column, such as discovering the function of the cord through experiments of "pithed" frogs which resulted in the death or immobilization of the specimen, revealing that it was involved in the control of movement and modulated bodily function (Bown, Gonzales, et al., 2017). Da Vinci even specifically states in his writing of the Anatomical Manuscript A that "the frog instantly dies when the medulla of the spine is perforated; and previously it lived without head, heart, or internal intestines. Here therefore appears to lie the foundations of movement and life" (Mazzarello, 2010). Both quantitative and qualitative data has shown da Vinci's impressive accuracies with the spinal cord solely through empirical observations showing that these findings display the near accuracy da Vinci achieved from the 15th century, suggesting that his works of the spinal cord have had a great impact on the knowledge we have today. His work on the cranium has a similarly high score that is classified to represent the anatomically correct model, with qualitative data further supporting this evidence. Even though his SSIM score of 0.977 is not classified as "excellent," the resemblance between his sketch and the anatomically correct model is nearly identical, contributing important findings and knowledge to our modern knowledge. While investigating the skull, Leonardo would use innovative techniques such as injecting molten wax in the skull to accurately map internal spaces inside the cranium that wouldn't be perceivable from the outside to pinpoint specific sinuses and cavities in the structure (Clayton, Philo, 2012). By doing so, he would have a greater understanding of specific locations of parts of the skull, including the supraorbital notch, fossa of the lacrimal sac, the canine fossa, the oblique line of the mandible, and mental foramen (Apuzzo, Khan et al., 2016). With the technology available during the time, it is important to acknowledge the great extent of accuracies that da Vinci had been able to pinpoint through creative improvisation, contributing to the parts of the axial skeleton we know today seen in the reliable SSIM score of 0.95 (Table 5) as well as his findings. The result I was surprised with the most was the data pertaining to the thoracic cage, as it had an unremarkable low score of 0.152 (Table 5).

Although there could have possibly been an error on my end with miscalculation and proper conversion, qualitative data provides potential reasoning for why the thoracic cage isn't as accurate as his other findings. Recent studies have shown that there is a huge difference in both lung and volume of the rib cage between females and males as well as varying ages (Bellemare et al., 2003). During his bodily dissection at the crypt of Santa Maria Nuova, da Vinci dissected more than 30 bodies of both genders and all ages, suggesting that he could have been exposed to all varying types of thoracic cages (Perloff 2013). It is possible that da Vinci had multiple references from different bodies while creating his sketch for the thoracic cage, explaining the

reasoning why it would differ from the anatomically correct, specifically male, cage. Even though he had a set basis of correct structure such as the false ribs, sternum, and manubrium drawn, specific positioning and spacing were not anatomically correct to be graded with a higher SSIM score.

Limitations

While gathering data, a limitation that interrupted the collection of my quantitative data was the initial conversion rates that the SSIM programming gave to me. By just inserting the raw image of scans from the Anatomical Manuscript A, the original SSIM program would register low scoring due to the fact many outside factors would affect it, including sketches, lighting, and small details that would hinder the overall structure that I was focusing on. Although I resolved this problem from editing and filtering out the discrepancies, another limitation that stopped me from examining on a closer accuracy was obtaining other sketches that pertain to similar to his depictions of the axial skeleton. Due to the fact that I am a beginner in coding, I was only able to use the very basic SSIM programming that was best for me to understand and operate. This limitation prevented me from getting the closest accuracy possible with the results, as if I were to be able to code a more complex program, I would have gotten more precise numbers and even pinpoint the accuracies and faults in da Vinci's sketches compared to the modern anatomical diagrams. Throughout my study, only three pieces throughout the Anatomical Manuscript A focused on the axial skeleton, which gave me a very limited view on da Vinci's interpretations and findings from his entire life of the skeleton. If provided more, I would have been able to collect different perspectives of data, and perhaps even infer da Vinci's inconsistencies and accuracies.

Closing

In conclusion, my findings highlight the remarkable accuracy of Leonardo da Vinci's anatomical sketches, particularly regarding the spinal cord and cranium, where both quantitative and qualitative analyses demonstrate a high degree of similarity to modern anatomical models. His innovative methods, such as the use of molten wax injections and empirical experimentation, allowed him to uncover key anatomical structures and their functions with striking precision despite the technological limitations of his time. While some discrepancies, such as those observed in the thoracic cage, suggest possible influences from multiple body references, they do not diminish the overall significance of his contributions. Not only should da Vinci be recognized for his findings of the axial skeleton, but also appraised for the impending accuracies that hint his influence of modern day anatomy and knowledge in the 21st century. Information about the vertebral axial skeleton had not been recorded until the 18th century, with da Vinci's Anatomical manuscript being released in 1510 (Williams 2020). It is important to keep in mind that during this time period, da Vinci solely relied on empirical analysis and observations with no medical tools available to him during his dissections in the crypt of Santa Maria Nuova (Heydenreich 2025). The accuracies of the diagram to his findings with quantitative data in the

16th century with the lack of information on the axial skeleton during the time insinuates the fact that da Vinci greatly contributed and influenced our knowledge on the axial skeleton in the 21st century, backed up qualitative data among his several findings with the vertebral column, the cranium, and the spinal cord. Da Vinci's meticulous observations laid a foundation for modern anatomical understanding, reinforcing the lasting impact of his work on contemporary medical and scientific knowledge. Da Vinci's public image is often stereotyped under an artist, with a general amount of society referring to him as "the guy who made the Mona Lisa" (Mussio 2023). However, my research clearly represents otherwise as he shouldn't only be categorized among the title of an artist, but a great anatomist that has contributed to the knowledge of the axial skeleton today, as well as many other revolutionary finds for medical advances in the 21st century. Unfortunately, due to feasibility purposes in my research, I was only limited to the research of the axial skeleton in anatomy specifically. However, I encourage further exploration into his advances of not only medical topics, but also scientific, technology, mathematics, and even embracing revolutionary transformations in art. It would be a disservice to limit da Vinci to the label of an "artist," as he accomplished great influence on our modern knowledge today. As a researcher, I would like to urge my fellow peers to further investigate older works of da Vinci that haven't been examined, such as his blueprints for technology and engineering, or uncoded manuscripts for greater projects. As we know of, da Vinci has accomplished many great things and discovered so many informational factors that led us to the knowledge we know today. If we continue investigating further in his works, it may even guide us to discovering something new.

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The War That Transcended Traditional Diplomacy: Exploring Vietnam's Enduring Impact On U.S. Foreign Policy By Adam Jishi

Abstract

This essay explores how the Vietnam War reshaped American diplomacy and left a legacy that continues to influence foreign policy today. It examines the Civil Operations and Revolutionary Development Support (CORDS) program, an experiment in merging military and civilian efforts to gain the support of local populations. Although CORDS represented an innovative attempt at "hearts and minds" diplomacy, its reliance on coercive tactics and its inability to secure lasting trust limited its effectiveness. The analysis then considers how lessons from Vietnam reappeared in Afghanistan, where Provincial Reconstruction Teams echoed CORDS' integrated approach but faced many of the same obstacles. By comparing these two conflicts, the essay shows that U.S. diplomacy evolved away from rigid ideological frameworks and toward a more pragmatic, realpolitik style of engagement. Vietnam stands as a turning point that revealed both the potential and the pitfalls of blending development with counterinsurgency, and its legacy continues to shape how the United States approaches international crises.

Introduction

In his short story collection depicting his Vietnam War experiences, Tim O'Brien writes, "I am a coward. I went to the war" (O'Brien 39). In this passage, O'Brien captures the ambivalence many American soldiers grappled with in fighting a war they did not necessarily believe was just. Still, his retrospective writing also indicates the difficulty of evaluating such a pivotal moment in American diplomatic and military history. In Vietnam, American involvement stemmed from Cold War anxieties about communist expansion, as the United States sought to support South Vietnam against the Soviet-backed North. The war escalated in the 1960s with massive American troop deployments and bombing campaigns, though the U.S. faced staunch resistance and guerilla-style attacks that contributed to an impossible situation. Following intense domestic pressure, the war officially ended for the U.S. with the 1973 Paris Peace Accords, although North Vietnam conquered the South in 1975 and unified the country under communist rule. The failure of American action in Vietnam exposed the limits of traditional military intervention and the need for a more integrated approach that understood local cooperation and support. Recognizing this need, the U.S. integrated foreign practices in previously unforeseen ways, most notably through the Civil Operations and Revolutionary Development Support (CORDS) program, which combined military operations with diplomatic and international developmental efforts at an unprecedented scale. For Vietnamese locals, CORDS meant increased U.S. and South Vietnamese government involvement in rural areas through village security forces, infrastructure projects, and propaganda as part of an overall American strategy that sought to win "hearts and minds" (Andrade). CORDS represented a significant shift from American diplomatic practices preceding the Vietnam War, subsequently defining contemporary diplomatic practices. While CORDS has had a lasting impact on contemporary American diplomacy, emphasizing civilian engagement, its ultimate failure (alongside the inability of

American objectives in Vietnam more broadly) catalyzed a transformation in the Foreign Service's diplomatic frameworks from ideologically motivated to more pragmatically driven.

The CORDS Program

The CORDS program blended counterinsurgency initiatives with military efforts that embodied "expeditionary diplomacy," or deploying a specialized force overseas for a defined mission and time frame before returning home (The Foreign Service Journal 20). This integration was revolutionary because the United States Foreign Service worked under a unified command that engaged with rural communities in a novel way. Through CORDS, U.S. personnel collaborated with South Vietnamese officials to establish village security forces, including the Popular Forces and Regional Forces, which aimed to protect impoverished rural populations from Viet Cong influence (U.S. Army Center of Military History). The program also invested in infrastructure projects, including roads, schools, and healthcare facilities, fostering economic stability and strengthening local allegiance to the South Vietnamese government. However, CORDS' counterinsurgency efforts, notably the Phoenix Program, sought to dismantle Viet Cong networks by eliminating suspected insurgents. This strategy resulted in both compliance and fear among the local population. Many Southern Vietnamese resented the program's coercive tactics, viewing it as quasi-colonial control rather than genuine American concern for Vietnamese well-being (Montague 21). Despite these shortcomings, by focusing on local needs to support the ultimate objective of defeating the communist north, American foreign policy synthesized military and civilian strategies in an unprecedented way, as illuminated by current Air Force Office of Special Investigations Commander Amy S. Bumgarner: "CORDS merged the once separate civilian and military pacification efforts into a program that may have been the only truly integrated civilian-military command in U.S. history" (Bumgarner 2). The emergence of this civilian-centered approach makes clear how Vietnam transformed the foreign service and its methods into an organization that considered civilian engagement strategies in tandem with rather than entirely separate from military strategy.

From Vietnam to Afghanistan

This approach to nation-building has significantly shaped many American foreign engagements in the post-Vietnam era, especially in Afghanistan. In the aftermath of the 9/11 attacks, the U.S. launched Operation Enduring Freedom to dismantle al-Qaeda and remove the Taliban from power in Afghanistan (9/11 Commission Report 337). Though it began as a counterterrorism initiative, American involvement in Afghanistan evolved into a long-term nation-building effort, mirroring in many ways the American attempt to prop up South Vietnam decades prior. Similar to the CORDS program, the Provincial Reconstruction Teams (PRTs) combined military and civilian initiatives to stabilize local communities and counter Taliban influence (Institute for the Study of War). PRTs aimed to provide security and develop local governance structures while collaborating with local leaders to give legitimacy to the new Afghan government (NATO Review). However, like Vietnam, these efforts were met with

skepticism and resistance from the local population, many of whom viewed American intervention as merely foreign imposition from a government with ulterior motives. For example, just as the Phoenix Program in Vietnam attempted to neutralize Viet Cong networks, counterinsurgency initiatives in Afghanistan, including night raids and targeted drone strikes, often alienated civilians and undermined the legitimacy of the American-backed government in Afghan eyes (CIA FOIA). Ultimately, while the integrated civilian-military approach introduced during the Vietnam War became a defining feature of American diplomacy in Afghanistan, it also suffered similar pitfalls. The fall of Kabul to the Taliban in 2021 following President Biden's decision to exit Afghanistan, in all of its chaos, echoed the fall of Saigon in 1975 and underscores the limitations of American nation-building efforts. Though the experience of the Vietnam War shaped contemporary American diplomacy, a comparative analysis of Vietnam and Afghanistan exposes the American Foreign Service's failure to learn from its past mistakes while implementing similar strategies.

Toward Pragmatic Diplomacy

While CORDS left a lasting mark on American diplomacy by emphasizing civilian engagement, it more broadly contributed to a shift in U.S. diplomacy from being based on ideological commitments to a more pragmatic and strategic approach. Andrew Krepinevich has argued that though CORDS saw some tactical successes in reducing Viet Cong influence in targeted areas, it ultimately failed to win over the broader population, who viewed the U.S. as unreliable and self-interested (Krepinevich 213). CORDS's failure to secure Vietnamese allegiance, despite economic aid, governance reform, and development of rural areas, illuminated the futility of instilling local populations with American Cold War ideological commitments against communism. The failure of counterinsurgency efforts to create sufficient local support resulted in a new understanding of international relations during the Vietnam War's final years.

This transition became increasingly evident during the Nixon administration in the late 1960s and early 1970s, as President Nixon pursued a policy of "detente" and sought to improve strained relations with China and the Soviet Union. Rather than approaching the Cold War as a zero-sum ideological struggle, Nixon's policy of detente sought global stability through pragmatic engagement and dialogue, as he became the first American president to visit China and establish formal relations with a communist government (history.com). During the final years of the Vietnam War, this shift to a "realpolitik" approach to international relations drove American diplomatic engagements in the decades following the Vietnam War and into the 21st century. For example, during the 1973 Yom Kippur War, the U.S. pursued a balanced approach that included pressuring Israel, its Cold War ally, to accept a ceasefire while also maintaining relationships with the Arab states and the Soviets to prevent regional destabilization (history.com, American Pageant). This pragmatic approach to international relations continued into the 21st century, particularly concerning American engagement in East Asia. While American leaders frequently criticize China's human rights record, authoritarian rule, and unfair

trade practices, economic interdependence has led to a more strategic engagement strategy. Despite growing tensions over trade and military expansion in the South China Sea, the Obama administration's 2015 U.S.-China Climate Agreement demonstrated a willingness to cooperate with Beijing on global challenges despite ideological differences (The White House). Similarly, Trump's direct negotiations with North Korea in 2018 during his first administration, including the historic meeting between Trump and Kim Jong-un, reflected a pragmatic approach that set aside ideological and political differences that would have made direct engagement impossible in the pre-Vietnam era.

Conclusion

American engagement in Vietnam, especially the CORDS program, had lasting impacts on the Foreign Service's legacy by implementing a policy of civilian engagement and triggering a shift from ideological commitments to pragmatic considerations as the basis of foreign policy positions. Some argue that the U.S. has taken such an extreme approach in recent years. President Trump has adopted punishing tariffs against allies and voted with traditional adversaries at the United Nations to improve the U.S.'s standalone geopolitical and economic situation. Contemporary disagreements over President Trump's approach to international relations complicate Vietnam's legacy. Tim O'Brien wrote in *The Things They Carried*, "I survived, but it's not a happy ending" (O'Brien 40). Just as O'Brien's memoir suggests that survival does not guarantee resolution, the legacy of Vietnam endures in American diplomatic history, reminding us that shifts in strategy do not always culminate in clear victories but rather ongoing struggles over the role of the U.S. in global affairs.

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Layered ASL Gloss (LAG): A Framework for Encoding ASL's Non-Manual Grammar

By Adrian Wang

Abstract

American Sign Language (ASL) is often represented through gloss, where ASL is directly translated into English, and word order is preserved. Although useful, gloss fails to capture ASL's complex non-manual grammar, leaving many learners oblivious to ASL's complexity. This paper proposes *Layered ASL Gloss (LAG)*, a new framework for capturing ASL's non-manual grammar alongside lexical signs. LAG categorizes and lists out the most common morphemes for each of the categories of non-manual grammatical, inflectional, gestural gradient, prosodic, mouth, and affective morphemes. Furthermore, LAG provides a music-score-like structure in which the simultaneity and nuance of these morphemes can be understood intuitively and visible in writing. While LAG cannot fully represent spatial classifiers, role shift, or gradient subjectivity, presenting LAG alongside video can fill these gaps. Rather than a true orthography, this paper emphasizes that LAG finds use as a teaching and analytical tool, serving to help English learners better understand ASL and making non-manual grammar accessible to learners, educators, and researchers.

Introduction

ASL is a rich and complex language; however, the differences between ASL and spoken languages present significant challenges in translation and communication. Due to ASL's complex grammar, hearing learners and new practitioners of ASL often are unable to grasp the nuances of meaning inherently encoded in signs when given written instructions. Especially for the purpose of instructing Deaf children and their parents, a system that is accurately able to encode the non-manual meanings in signs, while maintaining intuitive meaning to English speakers, is crucial (Supalla, Cripps, & Byrne).

There are many existing systems with which ASL can be expressed; however, the current standard for written communication for ASL learners is a glossing system, where ASL is directly translated into English while maintaining the same word order. However, this system is limited as it can only describe the exact meaning of the sign, and thus is unable to explain much of the nuanced grammar of ASL. As such, there is a need and a niche for a language system that can both communicate the nuanced grammar systems of ASL and also contain information intelligible to an English or spoken-language practitioner.

This paper attempts to fill this niche by characterizing and categorizing these morphemes so that they can be used in conjunction with ASL gloss to build a more comprehensive writing system, while maintaining relative ease of use and intelligibility for ASL learners.

Aside from ASL gloss, there are existing writing and recording systems for ASL. The most complete and preferred method for Deaf people to record their language is video, as it can fully capture the nuances of the language. Video is also often used in tandem with ASL gloss, as the gloss allows the learner to understand the meanings of the signs themselves while the video

displays the non-manual grammar of ASL. However, a major fault with this method is that new learners of ASL often don't know what to look for in non-manual markers and don't understand the associated meanings of these markers.

Several other writing systems have been developed to describe sign language, each with varying depth and complexity. William Stokoe developed Stokoe Notation, a system in which he broke down signs into 3 “phoemes”: dez, meaning designation or handshake, tab, meaning tabula or location, and sig, meaning signation or movement (Maher and Sacks). SignWriting is an “iconographic,” or pictograph-like language, built up of symbols that build a simplified image of a signer (Grushkin). Finally, HamNoSys is a complete way of describing signs and ASL's grammar. In a fashion similar to that of the International Phonetic Alphabet, it notes all meaning-encoding features of the language, but results in long and unwieldy strings of symbols (Hanke). These three systems are great for describing the features of a sign, and may be able to encode non-manual modalities, but they only describe the sign itself and thus hold little meaning to English-speaking learners. Although these systems do include basic non-manual morphology, these descriptions are inadequate to properly describe ASL's grammar.

Framework

To incorporate the highly layered, simultaneous grammar of ASL, this paper builds a framework referred to as “Layered ASL Gloss (LAG)” resembling a music score, with different “instruments” or morphemes layered over one another, and each occurring simultaneously (see fig. 1).

The bottom layer holds lexical information, or direct translations of ASL, in a manner very similar to that of ASL gloss. Above this layer are the various categories of non-manual markers; Since these markers occur simultaneously to the lexical/manual markers and have no fixed start and end time, they are written with a line which indicates how long the marker lasts, as well as an abbreviation at the end to indicate what marker was used (fig. 1). The following layer holds inflectional morphemes that slightly change the meaning of the root (i.e., pluralization, habitual actions). The third layer characterizes gestural gradient information, characterizing things on a continuum, like weight, size, or time. The fourth layer contains prosodic information that marks timing, rhythm, grouping, or emphasis (i.e., pausing, holding signs, leaning). The fifth layer contains mouth morphemes, which modify a sign's meaning by indicating size, intensity, manner, or descriptive quality (i.e., “cha”¹⁴² for exaggeration, or “thh”¹⁴³ to show clumsiness or forgetfulness). The final layer contains affective morphemes, or facial/body expressions that add emotional tone rather than formal grammatical meaning. A sub-layer, below the lexical information, could also be included to describe the phrase's approximate translated meaning in English.

¹⁴² The mouthshape made when one makes the sound cha.

¹⁴³ The mouthshape made by putting one's tongue in between their teeth.

Many accepted conventions expand upon this base system. The conventions that are included in LAG are the following:

1. Indices, or (IX), which describe the way in which ASL tracks references as points in space. IX-1 refers to a first-person reference, IX-2, a second-person reference, and IX-3, a third-person reference. If there are multiple references in the same grammatical person, a letter should be appended to the end of the reference (i.e., IX-3a) to differentiate between each reference (Mark).
2. Classifiers that directly describe an object or a description of the object are glossed as CL: + handshape/description (Belsky & Greene-Szmadzinski). For example, a flower would be glossed as “CL:FLOWER,” and the classifier describing a long, thin object would be glossed as “CL:LONG-THIN-OBJ.”
3. Words in ASL that are fingerspelled (written out letter-by-letter) are written with each letter separated by dashes (Belsky & Greene-Szmadzinski). For example, the word “bus” would be glossed as “B-U-S” if the fingerspelled variant of the sign was used.
4. Compounding in sign language is when two signs are combined into a different sign with a new meaning. The glossed words are written in the order they are signed, separated by a caret (i.e., THINK^SAME → AGREE) (Meir, Aronoff, Sandler, & Padden).
5. Signs that cannot be directly translated into a single English word can be translated into multiple English words, separated by a hyphen. For example, TAKE-CARE-OF, for the sign “to look after” (Schermer).
6. In ASL, a signer telling a story can embody their character and act out their actions in a manner known as “role shift.” Although the movements of the person cannot be described fully, to indicate a role shift, RS: + a description of their general actions.

We also included a group of five major non-manual grammatical morphemes in the lexical layer, as they have sentence-wide meaning (fig. 2). These are bound morphemes that affect the entire sentence and can be compared to a key signature; thus, they are placed at the beginning of the sentence in curly braces, “{ }.”

Morpheme	Function	Non-manual Marker	Example (Gloss)
Y/N-Q	Yes/No Question	Raised brows, lean forward	YOU LIKE APPLES?
WH-Q	Wh-Question	Furrowed brows	YOU LIKE WHAT?
NEG	Negation	Headshake	NO, I DON'T LIKE APPLES
COND	Conditional	Brow raise over subordinate clause	IF I GO, I EAT APPLES
TOPIC	Topic Marker	Raised brows + pause	APPLES, I LIKE

Fig. 2. A list of the most common non-manual grammatical morphemes. Adapted from Lifeprint (n.d.).

Put together, the lexical information of an ASL sentence could be encoded in a fashion resembling fig. 3:

Lexical: {Y/N-Q} IX-2 THINK^SAME IX-1 CL:LONG-THIN-OBJ LIKE?
Meaning: Do you agree with me that you like this pencil/pen (object)?

Fig. 3. An example of lexical morphemes being formatted in the LAG system.

Inflectional Morphemes

Although sign languages are less sequential and linear than spoken languages, they still maintain rich inflectional systems. These systems tend to be simultaneous, meaning that they directly modify verbs through a spatial/directional aspect rather than through an affix.

Inflectional Morpheme	Use / What It Marks	Gloss Convention/Shorthand
Verb Agreement	Marks the subject → object relations by moving from the location of the subject to the object.	Grammatical person→grammatical person, i.e., 1→2 or 3a→3b
Plurality (Reduplication / Sweep)	Repetition or sweeping movement of a sign to indicate more than one.	PL.
Aspect (Temporal Inflection)	Modifies verb movement for duration, frequency, or manner of action.	Use HAB for a habitual action Use CONT for a continuous action.
Distributional Inflection	Repetition of a sign in different directions/locations to show distribution to multiple referents.	If something is being done to each object in a category, use “→EACH.” If it is being done to everything, use “→ALL.”
Negation	Some verbs inflect with a negative tone; this can also be indicated with a head shake.	NEG

Fig. 4. Inflectional morphemes in ASL (adapted from Aronoff, Meir, & Sandler; Valli, Lucas, & Mulrooney; Baker et al).

Inflectional morphemes could be used to modify lexical information in a manner similar to that of fig. 5:

Inflectional: HAB	2→1	PL
Lexical: STUDY	GIVE	BOOK PLEASE
Meaning: I study (habitually), give me the books, please.		

Fig. 5. An example of inflectional morphemes being formatted in the LAG system.

Gestural Gradient Modifiers

Since ASL is a spatial language, many conditions can be communicated on a scale or gradient (which is described by the size or length of the gesture). They are continuous and are often iconic, meaning that the form resembles meaning (i.e., larger movement = larger object).

Although these modifiers are described as manipulations rather than discrete morphemes, they are distinct modifications to the form and meaning of a sign; however, the scales are often subjective and vary between persons.

Modifier (type)	Manipulation (form)	Meaning effect	Shorthand (+/-)
Speed modification	Signing faster or slower than the default	Urgency, effort, or gradual action	SPD
Endpoint/contact deletion	Omitting the final contact/closure of a telic sign	“Almost” / incomplete action	FINISH
Hold/lengthening	Sustained hold or longer static phase	Emphasis, intensification	HOLD
Path length/distance	Extending or shortening the movement arc	Greater/lesser distance or extent	LONG
Amplitude/size of motion	Enlarging/reducing overall movement size	Magnitude, intensity, emphasis	MOVE
Size/shape depiction	Modifying handshake/movement in classifiers	Relative size/shape of objects	SIZE

Fig 6. A list of common gestural gradient modifiers, their meanings, and their shorthand forms. Adapted from Aronoff, M., Meir, I., & Sandler, W.; Sandler, W.; Kuhn, J.; Lu, J.; and Ferrara, L.

These sources describe gradient modifications in speed, amplitude, path, holds, contact, and size/shape depiction in sign languages.

The shorthand of these modifiers will generally take the form of the aspect/characteristic of which they are describing (as described in fig. 6) and a following number of 1-3 “+” or “-” signs depending on the extent to which the characteristic is expressed (see fig 7).

Gestural Gradient:	HOLD++	SIZE++
Lexical:	IX-1	LOOK CAT
Meaning:	I slowly looked/stared at the big cat.	

Fig. 7. An example of gradual gradient modifiers being formatted in the LAG system.

Prosodic Morphemes

Prosodic morphemes define the intonation, rhythm, and structure of ASL—essentially, the flow of a conversation. Although the way in which prosodic morphemes are expressed varies from person to person, prosodic morphemes are grammaticalized: they mark clause type, punctuation, and organization, and thus the meaning of the morpheme is more easily described, while describing form is more difficult.

Prosodic Morpheme	Form (signal)	Function / Meaning	Shorthand
Pause / Hold	Brief cessation of movement	Marks clause boundary; adds emphasis	PAU
Blink (prosodic blink)	Eyelid closure at the boundary	Marks break or completion of a unit; functions like punctuation	BLK
Head nod	Small nod at end of clause	Marks intonational boundary or agreement	HN
Lengthening¹⁴⁵	Final sign prolonged	Indicates phrase-finality or emphasis	LEN
Rhythmic stress	Extra force / faster tempo	Highlights a word/sign in discourse	STR
Prosodic lowering	Reduced size/speed at end of phrase	Marks closure; functions like intonational “downdrift”	LOW
Prosodic raising	Increased size/speed	Signals new unit; creates prominence	RAI

Fig. 8. A list of common prosodic morphemes, their meanings, and their shorthand forms.

Adapted from Baker, van den Bogaerde, Pfau, & Schermer; Sandler; and Nespor & Sandler. These sources describe prosodic structuring devices in sign languages, including pauses, blinks, nods, lengthening, and rhythmic modulation.

Prosodic morphemes can be placed over spaces or punctuation as they characterize flow and can affect the space between words (see fig. 9).

Prosodic:	BLK	LEN
Lexical:	IX-1 STUDY FINISH	IX-1 SLEEP.
Meaning:	I finished studying; I slept.	

Fig. 9. An example of prosodic morphemes being formatted in the LAG system.

¹⁴⁵ Although the form of the lengthening is reminiscent of a gestural gradient modifier, it functions as a prosodic morpheme

Mouth Morphemes

Mouth morphemes are conventionalized mouth movements and shapes that carry consistent, grammatical, and semantic functions. They are mostly bound, and they generally occur on a single sign, although exceptions exist. Many of these signs are intuitive and descriptive; for example, the “CHA” mouthshape and the “OO” mouthshape mean very large or very small, respectively (fig. 10). However, there are two other categories of less intuitive mouth morphemes: they can be adverbial, such as “TH” indicating that something happened carelessly, and they can be affective, as is the case with “MM.”

Mouth morphemes are especially dynamic, as they tend to begin or end between or during signs; however, the timing of the transitions from one mouth shape to another is typically carefully coordinated. For example, with “CHA,” the mouth reaches the final mouthshape at the same time the hands reach the final position of the sign; with “PO,” the gap between each hand or each finger closes while the mouth opens (Bickford). Due to the coordinated timings, mouth morphemes should be included with a line denoting when they start and end.

A few mouth morphemes also include body articulators, such as a head tilt in the “STA-STA” morpheme; however, these articulators should be described in the prosodic section to maintain simplicity (Bickford).

Mouth Morpheme	Semantics (General Meaning)	Short Gloss/Notation
AHH	Long duration (time/space); astonishment/shock	AHH
CHA	Very large size or quantity	CHA
CLENCH	Extreme degree (very, intense, painful, fast, dark, etc.)	CLN
CLENCH-TOPIC	Marks a pronoun as the topic of a sentence	CLN-T
CS	Near in time or space	CS
HALFLIP	Resignation, reluctance, annoyance; “putting up with”	HLF
MM	Normal, moderate, as expected	MM
MMM	Pleasure, enjoyment, satisfaction	MMM
M-M-M	Backchannel: mild surprise (“oh really?”)	M3
OO	Very small; light/pastel; amazed (context-dependent)	OO
PO	Very tiny, diminutive	PO
PRESSED	Careful, attentive, concentrated action	PRS
PUFFED	Large and round, fat	PUF

PUFFED-BLOW	Quite/very (long, far, many, exhausted); medium-high degree	BLO
SOW	Extremely, to the highest degree	SOW
STA-STA	With effort, exertion	STA
TH	Carelessly, clumsily, without control	TH

Fig. 10. A list of the most common mouth morphemes, their meanings, and their shorthand forms. Adapted from Bickford, J. A. Mouth morphemes in ASL: A closer look. Denton Independent School District.

When mouth morphemes are included in the LAG diagram, it is important to include the prosodic row so that the physical aspects of the mouth morpheme can be included (if they exist), and also each morpheme should have the length-defining line (see fig. 10).

Mouth:	___OO___	___MMM___
Prosodic:	PAU	LEN
Lexical:	CAT	EAT FISH
Meaning:	The tiny cat ate the fish with satisfaction.	

Fig. 11. An example of mouth and prosodic morphemes being formatted in the LAG system.

Affective Morphemes

Affective morphemes communicate a signer's emotional stance or attitude during an utterance. They are not grammatical, and they are not obligatory for an ASL sentence. Affective morphemes are bound and typically overlap with manual signs.

Many affective morphemes overlap with mouth morphemes, as "affective" describes the meaning of the morpheme, and "mouth" describes the morpheme's form. However, for the sake of this system, only non-mouth affective morphemes will be included under affective morphemes (shown in fig. 12).

Affective Morpheme	Form (Articulation)	Emotional Meaning	Shorthand
Raised cheeks + squint	Cheeks lifted, eyes narrowed	Determination, stubborn	DET
Eyebrows furrowed + sigh	Brows drawn together, exhale	Frustration, irritation	FRUS
Drooping eyelids	Eyes half-closed, relaxed	Fatigue, boredom	TIRE
Head tilt + soft eyes	Tilt sideways, relaxed gaze	Sympathy, compassion	SYM

Shoulder drop	Shoulders slump down	Disappointment, resignation	DSAP
Quick head shake (light)	Small side-to-side motion	Mild disbelief, playful “no”	DISB
Torso slump forward	Chest forward, loose posture	Exhaustion, sadness	SAD

Fig. 12. A list of the most common affective (non-mouth) morphemes, their meanings, and shorthand. Adapted from Sandler & Lillo-Martin; Baker, van den Bogaerde, Pfau, & Schermer; and Wilbur. These works describe how facial and body articulations in ASL encode affective stance independently from grammatical or prosodic functions.

Since affective morphemes are largely bound and normally overlap a sign exactly, a line isn’t necessary to indicate the duration of the morpheme, as shown in fig. 13.

Affective:	FRUS	DSAP
Lexical:	IX-1 TRY FIX COMPUTER	FAIL
Meaning:	I tried to fix the computer but failed.	

Fig. 13. An example of affective morphemes formatted in the LAG system.

Conclusions

Although this system seeks to comprehensively categorize the non-manual morphemes of ASL, some inherently physical aspects of ASL are impossible to describe. LAG inherently struggles with three-dimensional classifiers, such as the movement of a sign from referent to referent, as the location of the index in space cannot be described concisely or intuitively. This system attempts to resolve this by establishing a reference to the location and assuming any location of a similar grammatical person would imply the same meaning. Furthermore, role shift cannot be fully captured in LAG—at best, it can be described narratively, which risks different interpretations. LAG also struggles with the subjectivity of gestural gradient modifiers, where it is uncertain what the benchmark for “big” and “small” would be. Furthermore, LAG is only able to encode 7 different states for gestural gradient modifiers as opposed to the continuum that they typically exist on. Although the music-score format of LAG allows for morphemes to exist during and between words, it can’t capture the true continuity of morphemes and ASL’s resulting rhythm in the way that video does. As utterances get more complicated and have more simultaneous constructions (as with both hands signing and a high volume of layered morphemes), LAG’s specificity can cause a visual cluttering of the information and become hard to understand.

The most elegant solution for these issues is to include LAG in addition to a video. LAG allows one to recognize what body or facial expressions constitute non-manual morphemes, while video allows one to see exactly what movements make up that morpheme. Furthermore,

video resolves the lack of spatial information that LAG suffers from, allowing clear descriptions of three-dimensional classifiers, full descriptions of role shift stories, and the full continuum of gestural gradient modifiers.

Another potential obstacle to the implementation of LAG is resistance from the Deaf community. There are many criticisms of ASL gloss, particularly from schools of thought such as Grushkin's¹⁴⁶ who argue that existing glossing practices primarily benefit spoken-language practitioners, reinforcing English dominance and the mindset that ASL is little more than just a signed form of English. He also argues that normal ASL glosses fail to represent the non-manual grammar of ASL and thus can cause learners to ignore the complex non-manual grammar for speaking and hearing learners. Furthermore, Grushkin argues that ASL gloss use in the teaching of Deaf children causes English to become a crutch to ASL, interfering with intuitive acquisition of ASL. He emphasizes that ASL deserves a dedicated orthography, and emphasizes writing systems like SignWriting, Stokoe Notation, and HamNoSys.

However, as argued by Supalla¹⁴⁷ gloss doesn't need to be considered a true writing system, but should instead be seen as a tool. Along with video, it allows ASL and English literacy to be bridged, especially for English speakers learning ASL and Deaf children learning to read English. It also helps teach the topic-comment word structure of ASL, and teachers can make good use of ASL gloss as a tool to make ASL visible in print. Due to the changes made to ASL gloss in LAG, the issue of improper representation of ASL grammar is also mostly resolved—non-manual markers are very heavily emphasized in LAG, and LAG stays true to the grammar of ASL.

If seen through the context of a tool for teaching and learning, LAG, especially when used alongside video, provides a simple and intuitive model for English-to-ASL learning. By categorizing inflectional, gestural gradient, prosodic, mouth, and affective morphemes alongside lexical sides, it highlights the non-manual features of ASL that base gloss overlooks and gives learners a framework to understand intuitively how these morphemes fit into the language. In classrooms, teachers will be much more capable of communicating specific non-manual markers, allowing learners to more easily recognize patterns that they would otherwise dismiss as simple body language. LAG can also find use for researchers seeking to communicate ASL's simultaneity and complexity to readers without having to use pictures and/or complex writing systems. LAG's role in the community is not to replace native signing, but to serve as a bridge—helping teachers and learners better understand ASL while staying true to the language itself.

¹⁴⁶ Donald A. Grushkin, Writing Signed Languages: What For? What Form? *American Annals of the Deaf*, 161, 509–527. <https://doi.org/10.1353/aad.2017.0001>

¹⁴⁷ Supalla, S. J., Cripps, J. H., & Byrne, A. P. J. Why American Sign Language gloss must matter. *American Annals of the Deaf*, 161, 540-551. <https://doi.org/10.1353/aad.2017.0004>

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Evaluating the Impact of Sensor Configuration on AI Model Accuracy in Predicting Lower Limb Knee Flexion-Extension Movements By David Hong

Abstract

Accurate prediction of human lower-limb movements is essential for advancing assistive robotics, rehabilitation technologies, and exoskeleton design. This study investigated whether reducing the number of sensors could maintain or improve prediction accuracy while enhancing system simplicity and robustness. A single subject was equipped with two surface electromyography (EMG) sensors and two inertial measurement units (IMUs) placed on the right thigh and lower leg. Sensor combinations were systematically reduced across four configurations, and a supervised AI model was trained to classify walking, squatting, and stair climbing. Results showed that the minimal configuration of one EMG (Vastus Lateralis) and one IMU (lower leg) achieved perfect precision and recall across all movements, outperforming the full four-sensor setup. These findings suggest that more sensors do not necessarily yield better performance and may introduce noise or machine error. Identifying minimal, high-impact sensor sets can improve accuracy, robustness, and wearability in real-world applications.

Keywords electromyography sensors, inertial measurement units, knee-flexion movement, sensor configuration, human-motion analysis

Introduction

The ability to accurately predict human joint movements is a fundamental requirement in the design of advanced assistive robotic systems and wearable rehabilitation technologies. While the structural design of exoskeletons has advanced, quality-of-life (QOL) aspects still lag due to possible miscommunications between the exoskeleton and the human body (Yao et al., 2024). With AI models emerging as powerful tools, their integration with wearable sensors offers a pathway toward smoother human-machine interaction and improved QOL (Yun et al., 2020). Research shows that knee flexion and extension are fundamental for daily activities such as standing, walking, and stair negotiation, with studies demonstrating that tasks like gait typically require under 90° of flexion, while stair climbing and sitting may demand up to 120° or more. These findings highlight the critical role of knee joint motion in supporting essential functional mobility (Myles et al. 46, 2002). Accurate recognition of these movements is therefore central to mobility assistance, independence, and rehabilitation.

Electromyography (EMG) and inertial measurement unit (IMU) sensors are widely used in motion prediction (Yang et al. 2998, 2023). EMG captures neuromuscular activity, while IMUs measure kinematics such as acceleration and angular velocity. When combined, they offer a comprehensive view of human movement. However, the effectiveness of these systems depends not only on signal clarity but also on usability. While adding more sensors can provide richer data, it may also decrease comfort, limit mobility, and complicate setup. For real-world

applications, particularly in assistive robotics where long-term use is expected, striking a balance between prediction accuracy and system simplicity is essential (Esmatloo et al., 2022).

This study investigates how reducing the number of sensors affects AI-based classification of knee-related movements. A fixed placement of two EMGs and two IMUs on the right thigh and lower leg was used, and sensor combinations were progressively reduced to evaluate their effect on prediction accuracy using an artificial neural network. The participant performed functional tasks, including walking, squatting, and stair ascent, reflecting movements encountered in daily life.

By analyzing how prediction accuracy changes with fewer sensors, this work aims to determine the minimal yet sufficient sensor configuration needed for reliable classification on the two muscles: Tibialis Anterior and Vastus Lateralis. Such findings contribute to the development of assistive robotic and rehabilitation systems that are both effective and practical, enabling greater wearability without compromising performance.

Literature Review

Accurate and timely prediction of human joint movements plays a critical role in advancing wearable assistive robotics, particularly lower-limb exoskeletons designed to support or augment mobility. Among the range of modern sensing technologies, inertial measurement units (IMUs) have emerged as a leading option because of their portability, affordability, and strong ability to capture kinematic data and spatial orientation in real time. These advantages have made IMUs widespread in research and clinical practice. However, when integrated into lower-limb exoskeletons, IMUs face distinct challenges that limit their effectiveness and highlight the need for improved or complementary sensing strategies.

A fundamental limitation of IMUs in exoskeleton applications is their inherently reactive nature. IMUs register movement only once the user has already initiated it, which introduces unavoidable latency into the control loop. For lighter assistive devices, this delay may be manageable, but for heavy lower-limb exoskeletons that must actively drive motion, the lag is a serious barrier. These devices cannot be moved independently by the user, so assistance must be generated in synchrony with, or ideally in anticipation of, the wearer's intent. Studies consistently report delays of around 20 to 30 milliseconds between motion detection and actuation in IMU-based systems, caused by sensor processing and motor response times (Zhou et al., 2022). Though seemingly small, this delay disrupts the natural fluidity of lower-limb movement, reducing comfort and increasing fatigue. In more serious cases, latency can cause the system to stall: if the exoskeleton does not move, the user cannot move, leaving the IMU with no new data to record and no signal for the control system to predict.

Another source of difficulty is the vulnerability of IMUs to soft tissue artifacts (STAs). Because sensors are typically mounted on the skin, they may shift relative to the underlying bone during dynamic activity (Clément et al., 2018). These shifts distort estimates of joint axes and angles, degrading motion accuracy (Yousaf et al., 2023). Even when multiple IMUs are employed to mitigate the problem, errors persist. Comparative studies using motion capture and

IMUs have documented deviations of several degrees in knee flexion and extension, particularly during high-impact tasks such as stair descent or sit-to-stand transitions (Akhbari et al., 2013). This issue is especially important when IMU data is used to train AI models for predictive control, since errors during training propagate into the model's ability to generalize.

Electromyography (EMG) sensors, in contrast, offer a complementary advantage. EMG records the electrical activity of skeletal muscles, providing a window into neuromuscular activation that precedes observable motion (Caulcrick et al., 2020). Evidence shows EMG can detect movement intent significantly earlier than IMUs: one study reported EMG onsets occurring up to 138 milliseconds before inertial signals, and in some cases as early as 248 milliseconds prior to mechanical action, depending on which limb initiated the motion (Wentink et al., 2013). This anticipatory quality allows exoskeletons to generate assistance before the user physically moves, compensating for the latency issues inherent to IMUs. By aligning machine response with muscle activation rather than delayed motion data, EMG enables more seamless and natural human-machine interaction.

The most promising path forward lies in combining IMU and EMG data through multimodal sensor fusion. IMUs provide accurate kinematic feedback once movement is underway, while EMG supplies early indicators of motor intent. When fused, the strengths of each compensate for the weaknesses of the other, improving predictive accuracy, reducing susceptibility to drift or variability, and enabling more stable control (Wentink et al., 2013; Zhou et al., 2022; Guo et al., 2020). Nevertheless, this approach raises the question of sensor quantity. More sensors may provide richer data, but also risk introducing redundancy, noise, and discomfort. For example, overpopulating a muscle with EMG electrodes can obscure meaningful patterns and confuse machine learning models, ultimately degrading performance.

Despite increasing research in this area, the field still lacks standardized guidelines for how many sensors and which configurations achieve the best balance between predictive accuracy, usability, and wearability. This uncertainty is especially significant when designers are constrained to a fixed number of sensors for practical reasons.

This study seeks to address this gap by systematically evaluating the predictive contribution of a limited, strategically chosen sensor set. Specifically, it investigates a baseline configuration of two EMG and two IMU sensors placed on the Tibialis Anterior and Vastus Lateralis muscles for a range of functional lower-limb tasks. By analyzing the effect of sensor location and number on the prediction accuracy of knee flexion-extension, the research aims to provide actionable guidance for exoskeleton design. The results will inform practical trade-offs between sensor complexity and system performance, supporting the development of wearable devices that are not only accurate and responsive but also comfortable and intuitive for everyday use. Ultimately, such findings contribute to creating exoskeletons and rehabilitation systems that integrate smoothly with the body, enhancing mobility while preserving natural movement patterns.

Methods

Experimental Design Overview

This study evaluated how reducing the number of sensors affects AI-based movement classification accuracy. A full sensor array of two EMG sensors and two IMU sensors was used as the baseline. Across trials, the artificial neural network was trained and tested with progressively fewer sensors (removing one at a time) while keeping placement constant. Only one individual is used to wear the sensors; therefore, results may differ slightly depending on the individual wearing the sensors.

Sensors and Placement

EMG sensors: Important sensors that record surface electrodes for muscle activation, placed on the right Tibialis Anterior and Vastus Lateralis.

IMU sensors: placed on the right thigh and lower leg, it is used to record the axis values of the sensors.

Placement remained fixed across all trials to isolate the effect of sensor number.

EMG1 = Tibialis Anterior

EMG2 = Vastus Lateralis

IMU1 = Thigh, front facing floor.

IMU2 = Lower Leg, facing ceiling

Picture of positioning:

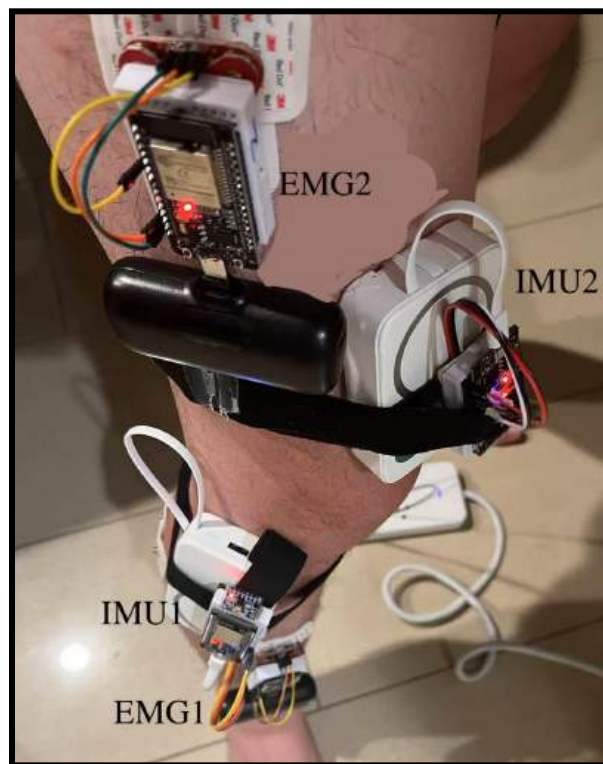


Figure 1: Picture of all 4 sensors on right leg

Movement Protocol

The participant performed three functional movements for each sensor condition:

- 1: Stair ascent at a consistent step rate
- 2: Bilateral squats to $\sim 90^\circ$ knee flexion
- 3: Walking at a natural pace

Each trial lasted 10 seconds, with data recorded every 100 ms. Each movement has a number classification set to it for labeling movements during model training and testing.

Data Collection & Processing

EMG and analog IMU outputs were recorded via Arduino Serial Monitor and stored in Google Sheets format. Each row signals one test for a specific movement with its number classification. For AI input, each sensor's data array was reduced to **mean (M)** and **standard deviation (SD)** values. Each EMG contributed 2 features (M, SD), while each IMU contributed 6 features (M, SD for the x, y, z axis). Thus, the full set yielded 16 features, which decreased as sensors were removed.

AI Training & Evaluation

A supervised classification model was trained using labeled datasets for each movement and sensor condition. Data were split into 10 training sets for each movement and 5 testing sets per movement. Model outputs were expressed as classification accuracy percentages, comparing sensor combinations from full (2 EMG + 2 IMU) down to single-sensor input.

Results

Classification Accuracy for Configuration 1: 2 EMGs and 2 IMUs

Precision Accuracy Output:

StairClimb	= Precision: 1.000	Recall: 0.800
Squatting	= Precision: 1.000	Recall: 1.000
Walking	= Precision: 0.833	Recall: 1.000

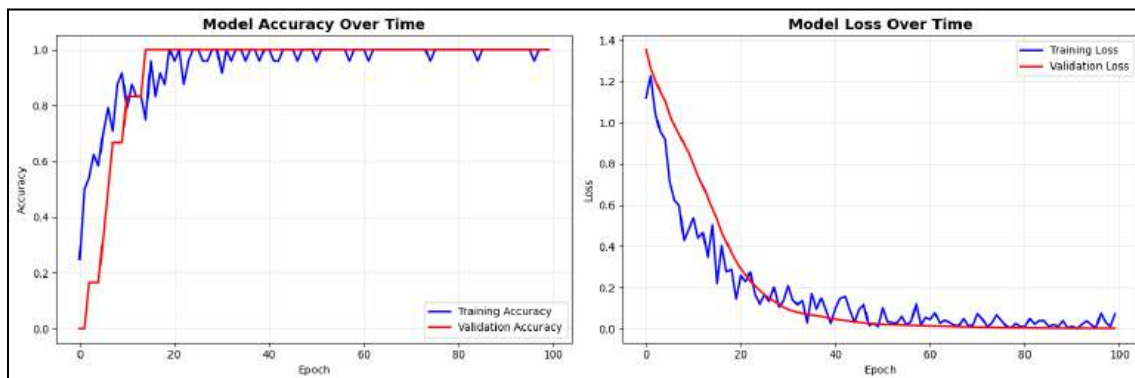


Figure 2: Training Data of Config 1

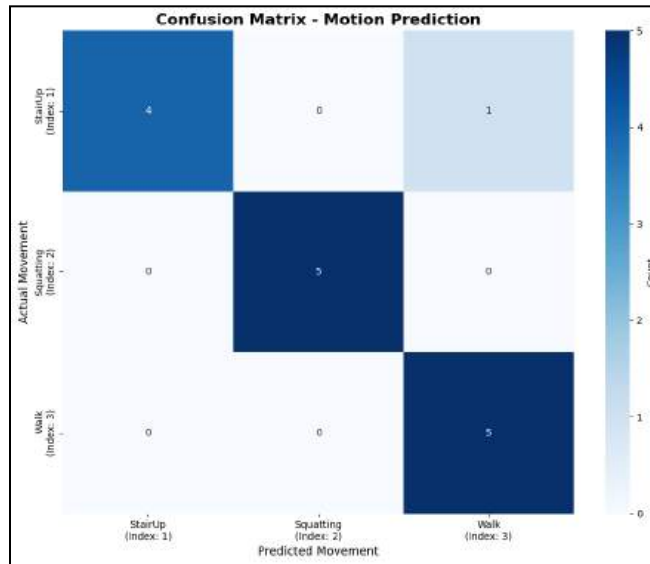


Figure 3: Confusion Matrix of Config 1

Classification Accuracy for Configuration 2: EMG 1 and IMU 1

Precision Accuracy Output:

StairClimb = Precision: 1.000 Recall: 0.800

Squatting = Precision: 1.000 Recall: 1.000

Walking = Precision: 0.833 Recall: 1.000

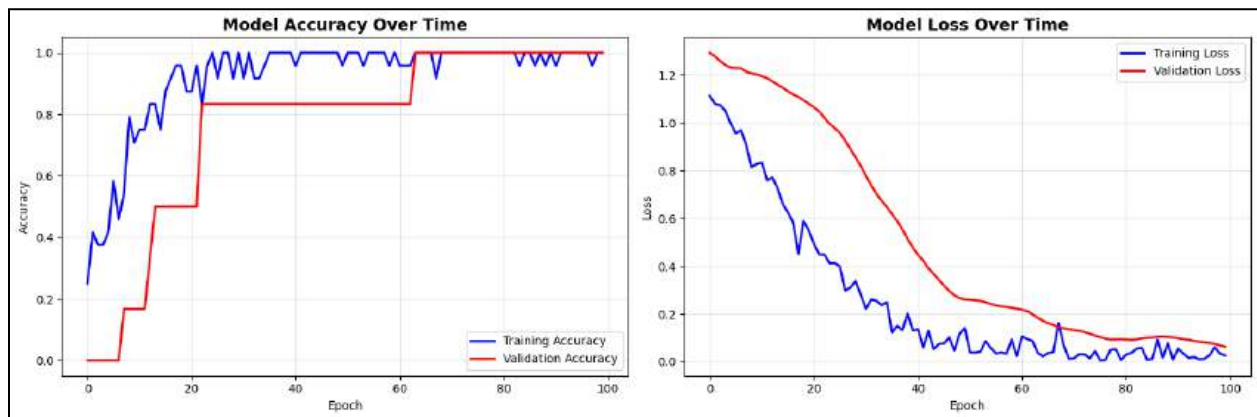


Figure 4: Training Data of Config 2

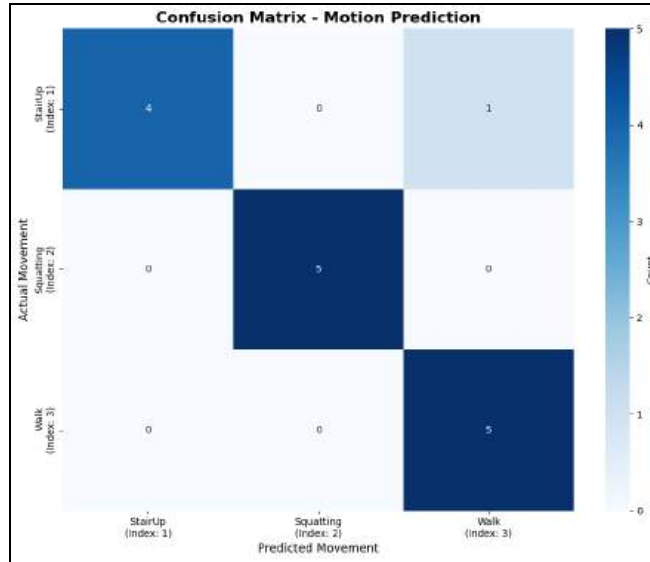


Figure 5: Confusion Matrix of Config 2

Classification Accuracy for Configuration 3: EMG 2 and IMU 2

Precision Accuracy Output:

StairClimb = Precision: 1.000 Recall: 1.000
 Squatting = Precision: 1.000 Recall: 1.000
 Walking = Precision: 1.000 Recall: 1.000

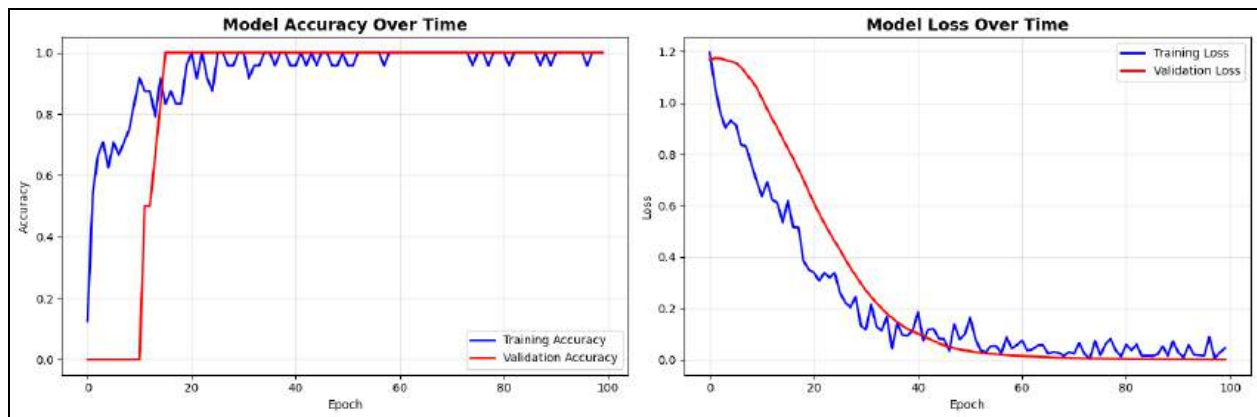


Figure 6: Training Data of Config 3

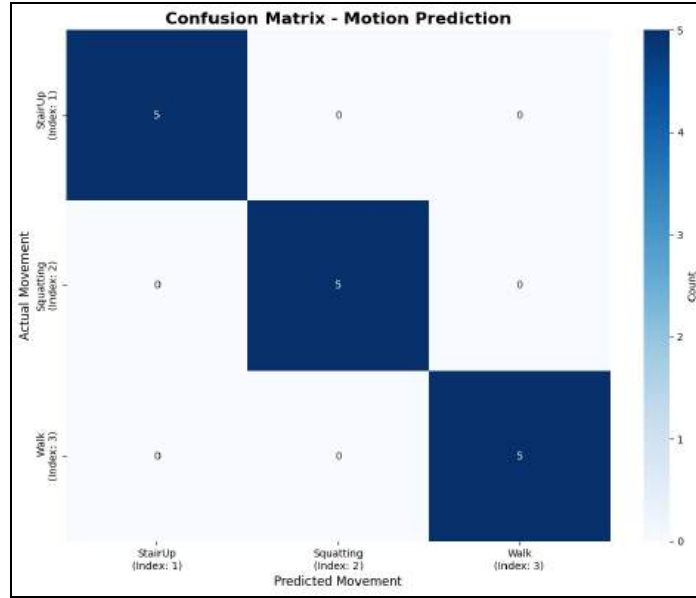


Figure 7: Confusion Matrix of Config 3

Classification Accuracy for Configuration 4: 1 EMG

Precision Accuracy Output:

StairClimb = Precision: 1.000 Recall: 0.800

Squatting = Precision: 0.833 Recall: 1.000

Walking = Precision: 1.000 Recall: 1.000

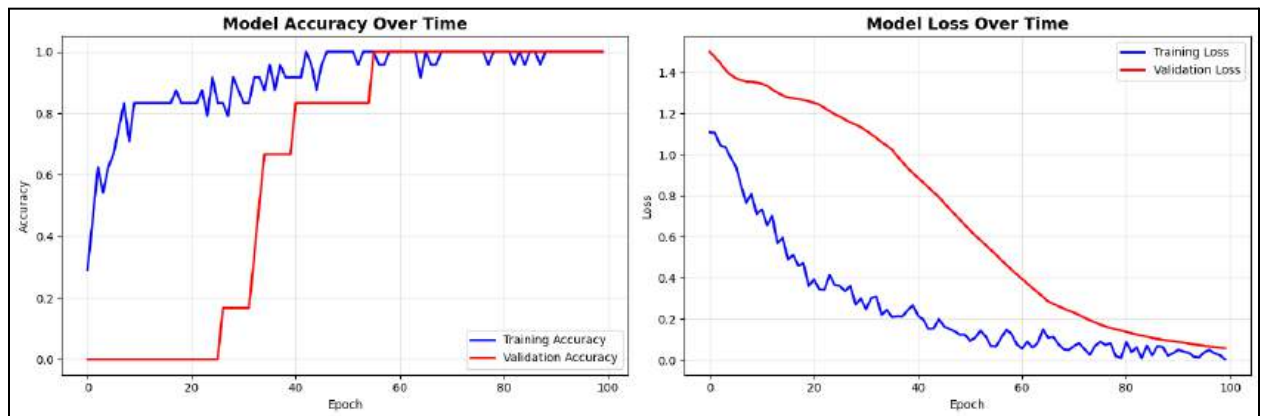


Figure 8: Training Data of Config 4

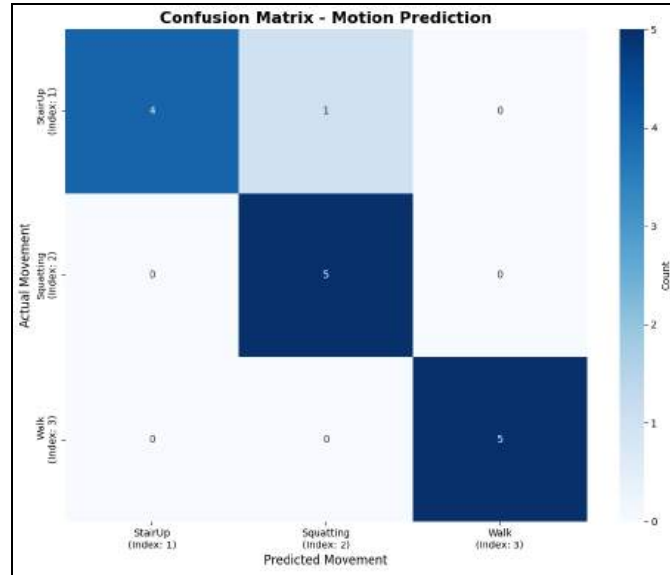


Figure 9: Confusion Matrix of Config 4

Discussion

Based on the systematic evaluation of four sensor configurations, the results provide clear evidence that the strategic removal of certain sensors can not only maintain but in some cases *improve* the accuracy of knee flexion-extension movement prediction, while also introducing critical considerations for system robustness.

The most significant finding is the performance of Configuration 3 (EMG 2 and IMU 2), which achieved perfect precision and recall (1.000) across all three movements: StairClimb, Squatting, and Walking. This configuration, which utilized only the Vastus Lateralis (EMG 2) and the Lower Leg IMU (IMU 2), outperformed the full sensor suite (Configuration 1). This suggests that for the 3 specific movements, the Vastus Lateralis muscle activity and the kinematics of the lower leg provided the most accurate signals, and that data from the Tibialis Anterior (EMG 1) and Thigh IMU (IMU 1) may introduce redundant or even noisy information that the model must filter out. However, it is also important to note the possible machine/human errors introduced into the AI that may have confused it.

On the other hand, Configuration 4 (1 EMG), which used only a single EMG, showed a noticeable dip in performance for Squatting (Precision: 0.833). It also showed a considerably larger time to accurately train the AI, showing that fewer sensors isn't always the best answer, as it can reduce AI efficiency despite similar results in the end. This decline highlights that the removal of all IMU data degrades the model's ability to precisely classify certain movements, highlighting the value of a hybrid EMG-IMU system over relying on the use of a single sensor type.

The confusion matrices and precision-recall metrics reveal a critical practical insight: a simpler, well-chosen sensor configuration (Configuration 3) can be more accurate and robust than a complex one. This has major implications for real-world application. From a reliability perspective, a system with fewer sensors is inherently less prone to machine error and sensor

failure. By identifying a minimal, high-impact configuration, the system's overall robustness and user compliance can be significantly improved, as it reduces the setup complexity and filters out the noise from excessive amounts of sensors.

Conclusion

In conclusion, this study demonstrates that "more sensors" does not automatically equate to "better performance." The removal of certain sensors from specific positions to create a minimal, optimal configuration (EMG 2 + IMU 2) enhances prediction accuracy and promises greater system reliability by reducing potential points of machine failure. This finding is crucial for developing practical, user-friendly, and robust wearable technology for rehabilitation and assistive exoskeletons, where simplicity and reliability are just as important as accuracy. Future work should validate these minimal configurations on a larger cohort and in real-world environments outside the lab to further stress-test their robustness.

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Psychological and Neurological Factors Shaping Patient Choices in Physician-Assisted Suicide By Arushi Sinha

Abstract

Physician-assisted suicide (PAS) is an emotionally and ethically complex practice in end-of-life care, currently legal in only a limited number of jurisdictions. This review examines how the psychological and neurological states of terminally ill patients, as well as the ethical perspectives of healthcare providers, influence decisions to pursue PAS. Sources were identified through targeted searches in Google Scholar, focusing on peer-reviewed literature in psychology, neurology, and medical ethics. Findings indicate that psychological factors such as depression, hopelessness, existential anxiety, and perceptions of being a burden, along with neurological impairments in cognition and executive functioning, can significantly affect decision-making capacity. Physicians' evaluations further highlight the role of untreated psychiatric conditions and cognitive decline in shaping requests for PAS, while moral distress and personal values influence healthcare providers' participation. These findings underscore the importance of standardized psychological and cognitive assessments, comprehensive palliative care integration, and institutional support for providers to ensure that PAS decisions are ethically grounded and genuinely autonomous.

Introduction

Physician-assisted suicide (PAS) is a medical practice in which a physician provides a terminally ill patient with the means, typically a prescription for a lethal dose of medication, to voluntarily end their own life (Miller and Meier 552). This decision is often considered when patients face irreversible conditions marked by intense suffering, diminished autonomy, or the anticipation of a loss of dignity. PAS is currently legal in select jurisdictions including Oregon, Washington, Canada, Switzerland, and the Netherlands, where it is regulated through legal safeguards, psychological assessments, and procedural steps to ensure patient competency and voluntariness (Mroz and Chambaere).

This paper argues that the psychological state of terminally ill patients and healthcare providers profoundly influences decision-making and emotional outcomes in PAS. Understanding the emotional and mental health dynamics on both sides of the decision is critical for informing ethical guidelines and legal proceedings, and ensuring compassionate and patient-centered end-of-life care, not only for informing ethical guidelines and legal procedures, but also for ensuring that end-of-life care is compassionate, patient-centered, and psychologically sound.

History and Legalization of PAS

PAS has a complex and controversial history. Its legalization, first enacted in Oregon through the 1997 *Death with Dignity Act* (Miller and Meier 552), marked a significant shift in end-of-life care policy. The law established a framework emphasizing autonomy, informed

consent, and mental competency. Since then, similar legislation has been adopted in other U.S. states such as Washington, California, and Vermont, and in countries such as Canada, the Netherlands, Belgium, Luxembourg, Spain, and New Zealand (Stukalin et al. E341).

However, resistance against PAS persists, rooted in religious beliefs, ethical objections, and fears of abuse or coercion. Legal safeguards, such as waiting periods, repeated requests, and mental health evaluations, have been designed to address these concerns and ensure that PAS is a voluntary and rational choice rather than a symptom of treatable psychological distress (Person et al. 85).

Patient Perspective: Psychological Dimensions

The decision to pursue physician-assisted suicide (PAS) is deeply influenced by a combination of psychological and existential factors, including fears of prolonged suffering, loss of control, depression, social isolation, and a perceived burden on loved ones. Studies show that untreated existential anxiety and depression, if unrecognized or untreated, can significantly increase the desire to end life (Grassi et al. 189; Worthington et al. 695). For example, a 2008 study by Breitbart et al. examined terminally ill cancer patients and found that those diagnosed with major depressive disorder were significantly more likely to express a desire for hastened death. Nearly 59% of patients with depression reported a high desire to die, compared to just 8% of non-depressed patients. The researchers emphasized that psychological distress, especially stemming from hopelessness, loss of autonomy, and demoralization, was a stronger predictor of wanting to die than physical pain (Breitbart et al. 259).

The impact of psychological state on PAS decisions varies widely by cultural, legal, and socioeconomic context. For example, in the Netherlands and Belgium, where PAS is legal and more socially normalized, patients report feeling less stigma and more open conversations with family and physicians (Beuthin et al. 125). In contrast, in the United States, state-level variation and stronger religious opposition can create psychological burdens like shame or secrecy, complicating the decision (Stukalin et al. E343).

This highlights how critical it is to address mental health symptoms in end-of-life care to ensure that the desire to die is not a manifestation of treatable suffering. Hence, psychological evaluations are often mandated to assess mental competency and emotional health (Grassi et al. 193). In addition to the four core dimensions of healthcare decision-making capacity—understanding, appreciation, reasoning, and expression of choice—clinicians rely on a combination of structured interviews and standardized tools. Commonly used assessments include the Mini-Mental State Examination (MMSE) and the Montreal Cognitive Assessment (MoCA) to detect cognitive impairment, and the MacArthur Competence Assessment Tool for Treatment (MacCAT-T), which is considered the gold standard for evaluating the ability to make informed medical decisions (Appelbaum and Grisso). Psychiatric evaluations often involve the Structured Clinical Interview for DSM-5 (SCID-5) to diagnose mood or anxiety disorders, while tools like the Beck Depression Inventory-II (BDI-II) and Demoralization Scale help measure depressive symptoms and existential distress (Robinson et al. 246). These assessments enable

clinicians to determine whether the patient's wish for assisted death arises from a stable and autonomous state or is instead influenced by treatable psychiatric or cognitive conditions. Mental health professionals, such as psychiatrists or clinical psychologists, conduct these evaluations to ensure that the decision is not compromised by untreated mental illness and that the patient retains the cognitive and emotional clarity needed for such a profound choice (Beuthin et al. 130).

Patient Perspective: Neurological Dimensions

Neurological function must also be considered when assessing one's decision to pursue PAS, as it may be compromised by disease progression, medication side effects, or chronic pain. Studies show that prolonged suffering alters brain chemistry, affecting areas tied to emotional regulation, decision-making, and perception of time and self-worth (MacDonogh 115). For instance, neuropathic pain or cancer-related fatigue can impair frontal lobe function, where executive decisions are processed. Neuroimaging studies using functional MRI (fMRI) and PET scans have shown altered activity in the prefrontal cortex, particularly the dorsolateral and medial prefrontal regions, in patients with chronic pain and advanced cancer (Neiffer and Stamper 148). These physiological disruptions may subtly impair patients' ability to weigh choices or maintain stable preferences, which is critical when evaluating requests for assisted death. Thus, pain not only reduces quality of life but may also cloud rational judgment.

Neurologically, conditions such as chronic pain, cancer-related fatigue, or neuroinflammation may impair cognitive clarity and executive function, undermining decision-making capacity in subtle yet significant ways (Neiffer and Stamper 150). Within this context, PAS raises the pressing issue of existential suffering, a non-physical yet deeply distressing experience rooted in fear, disconnection, or a perceived lack of meaning.

Physician Perspective: Emotional and Ethical Conflict

The decision to pursue PAS involves both the patient and the provider; physicians may wrestle with ethical dilemmas, conflicting professional values, and emotional strain. Some view PAS as an extension of compassionate care, while others feel morally opposed or emotionally unprepared to participate. These internal conflicts can affect physicians' willingness to support or refer patients to PAS, as many face unique emotional challenges—some view the practice as a compassionate extension of patient autonomy, while others experience moral distress, knowing the ethically appropriate action but feeling powerless to act due to institutional or personal barriers (Scotney et al. 801). Some physicians fear a “slippery slope,” where normalizing PAS could gradually expand eligibility beyond terminally ill patients to include those with chronic conditions, psychiatric disorders, or existential suffering, raising serious ethical concerns about weakening safeguards and blurring the boundaries of acceptable medical practice. Others express concern about becoming desensitized to death or facing backlash from peers or community members (Scotney et al. 803).

Studies show that burnout, empathy fatigue, and personal belief systems can reduce

physicians' emotional resilience, making them less willing or able to engage in the complex, emotionally charged process of physician-assisted suicide, and potentially leading to avoidance, moral conflict, or impaired judgment (Scotney et al. 804). Support systems such as ethics committees, peer consultation, and reflective practices can help doctors process these emotional experiences and make decisions aligned with both patient needs and professional integrity. Some ethicists and clinicians argue that existential suffering should be treated as seriously as physical pain when evaluating end-of-life choices. As such, comprehensive psychological care, including counseling, existential therapy, and psychiatric intervention, can serve as a powerful form of palliative treatment, potentially reducing the wish to die by addressing the emotional and spiritual pain that often underlies these requests.

Discussion and Conclusion

The psychological dimensions of physician-assisted suicide are central to understanding both its ethical justification and practical execution. Patients' emotional states—shaped not only by physical pain but also by existential suffering such as loss of meaning, fear, and depression—directly impact their desire to pursue PAS. Some ethicists and clinicians argue that existential suffering should be treated with the same seriousness as physical pain when evaluating end-of-life choices (MacDonogh 116; Chochinov 185; Ganzini et al. 583). Importantly, the impact of psychological state on PAS decisions also varies widely by cultural, legal, and socioeconomic context. For example, in the Netherlands and Belgium, where PAS is legal and more socially normalized, patients report feeling less stigma and more open conversations with family and physicians (Beuthin et al. 126). In contrast, in the United States, state-level variation and stronger religious opposition can create psychological burdens like shame or secrecy, complicating the decision (Stukalin et al. E344). Similarly, healthcare providers' internal conflicts, moral values, and emotional resilience influence their role in this deeply challenging process (Scotney et al. 805; Beuthin et al. 132).

Acknowledging the full complexity of these psychological dynamics calls for more compassionate, ethically sound, and patient-centered practices. This includes rigorous and empathetic mental health evaluations using standardized screening tools, such as the Patient Health Questionnaire (PHQ-9) and Hospital Anxiety and Depression Scale (HADS), which provide consistent, validated measures to assess psychological and cognitive soundness across jurisdictions (Ganzini et al. 490; Grassi et al. 194; Miller and Meier 556). Expanding access to comprehensive palliative and existential therapies integrated into end-of-life care is equally important. Such integration addresses not only physical symptoms but also emotional and spiritual distress, offering patients alternatives to PAS by alleviating existential suffering and enhancing quality of life (Kissane 1502; Puchalski et al. 643; Worthington et al. 697). Moreover, consistent training and institutional support are critical to sustaining healthcare providers' emotional well-being amid the moral complexities of PAS. Concrete measures such as structured debriefing sessions, professional counseling access, and peer support groups—programs already emerging in some palliative care settings (Hudson et al. 18; Meier et al. 735; Stukalin et al.

E344; Neiffer and Stamper 152)—can mitigate provider burnout and moral distress.

Moving forward, I advocate for the widespread implementation of standardized mental health screening protocols, the integration of existential and palliative therapies into routine end-of-life care, and the development of institutional resources to support providers' emotional resilience. Together, these reforms would ensure that decisions about PAS are truly autonomous, ethically grounded, and reflective of both medical science and human dignity.

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How Does the Timing of Exposure Affect the Long-term Epigenetic Changes Linked to Breast Cancer Across Generations? By Madison Shi

Abstract

Breast cancer is one of the most prevalent cancers among women. With genetic mutations such as BRCA1 and BRCA2 being known to contribute to breast cancer susceptibility, research shows that environmental exposures can influence breast cancer development through epigenetic modifications. Epigenetic modifications can alter gene expression patterns, leading to uncontrolled cell growth. While research shows that environmental exposures can influence breast cancer development through epigenetic changes, details regarding the timing of exposure to certain factors are unclear. In this review, exposure to environmental toxins during developmental periods are examined, as well as their transgenerational effects. Research has shown that epigenetic changes can be inherited, meaning that even though the offspring was not directly exposed to environmental toxins, there is still a possibility of developing breast cancer. Even low levels of exposure to environmental toxins can increase the risk of breast cancer. The father's diet around the time of conception is also important to ensure the offspring develops healthy mammary glands, which can reduce the offspring's chance of cancer. These findings contribute to a better understanding of breast cancer susceptibility, allowing for earlier detection and improved treatment techniques that may reduce the chances of breast cancer susceptibility.

Introduction

Cancer is one of the leading causes of death worldwide. Cancer progression refers to the development of a disease where cells grow and divide abnormally due to mutations made in the DNA. Malignant cells can then spread to other parts of the body and destroy normal body tissue. If not treated properly, cancer can lead to serious health complications, such as heart damage, or even death.

Breast cancer is the most common form of cancer amongst women, with approximately 1 in 8 women in the United States developing the disease in their lifetime (American Cancer Society, 2025). The incidence of breast cancer has increased by 1% each year between 2012 to 2021. One hypothesis is that this may be a result of the increased use of chemicals, which can alter gene expression (Manzoor et al., 2022). Nonetheless, early detection and increased screenings have helped increase the survival rate to 99% (National Breast Cancer Foundation, 2019). About 5-10% of breast cancer cases are due to the presence of BRCA1 and BRCA2 mutations. Despite this, most other cases of breast cancer are a result of environmental effects and lifestyle choices. Other factors can also increase the incidence of breast cancer, such as having a family history or inheriting certain epigenetic modifications (Mayo Clinic, 2025).

Epigenetics refers to how the environment affects gene expression without altering the gene sequence. Epigenetic changes affect the genes by turning them "on" or "off," meaning that the genes make protein in abnormal places, times, or levels. These modifications can result in the alteration of gene expression patterns and lead to uncontrolled cell growth (ref). The most

common way the environment can cause an epigenetic modification is by changing the DNA methylation which adds or removes chemical groups to regulate gene activity. Increased methylation turns genes off and reduces protein production, while demethylation turns genes on and increases protein production. Unlike genetic mutations, epigenetic modifications can be reversed and are shaped by factors such as environmental toxins, stress, and diet (Centers for Disease Control and Prevention, 2025). Epigenetic changes can occur before birth and determine each cell's function. A pregnant woman's actions and environment during pregnancy can therefore affect the epigenetics of the baby. Some of these changes may last for decades and make the baby more prone to certain diseases, including cancer (Bohacek & Mansuy, 2012).

Current research has established that epigenetic changes are often detectable before clinical symptoms are displayed (Aboud et al., 2023). However, this raises the question about how the timing of exposure to certain factors, such as chemicals or stress, can impact long-term epigenetic changes linked to breast cancer. This review will discuss the developmental periods, as well as the amount of exposure, that will have a transgenerational effect on breast cancer.

Discussion

Background of Epigenetic Mechanisms

Epigenetic mechanisms such as DNA methylation and histone modifications regulate gene expression by changing DNA accessibility. DNA methylation adds a methyl group, which silences genes by preventing them from being transcribed into proteins. This process is crucial for differentiating cells, allowing them to become specialized types like nerve or muscle cells. (Ospelt, 2022). In breast cancer, hypermethylation of tumor suppressor genes, such as BRCA1, can continue the development and progression of the disease. Because DNA methylation patterns are consistent amongst specific tumor types, they serve as biomarkers for the early detection of breast cancer (Hum & Lee, 2025).

Histone modifications refer to the chemical alteration of histone proteins, changing the structure of the chromatin. These modifications control how tight or loose the DNA is packaged. When histones are modified to loosen the DNA, the genes become easier to read, while modifications that tighten DNA make genes harder to access, turning them off. Histone modifications and DNA methylation are interlinked and work together to control gene expression. (Rose & Klose, 2014). An aberrant occurrence of these epigenetic mechanisms can lead to DNA damage.

DNA Damage Can Cause Harmful Epigenetic Changes

When DNA is damaged by radiation or chemicals, the cell activates DNA damage response pathways to repair it. The damage can alter sequences in nucleotides and express defective proteins. Unrepaired DNA damage can result in extreme mutations, which effects the survival of cells (Alhmoud et al., 2020). Previous research has shown that the increase in DNA damage is necessary, but not enough for tumor growth, while a decrease in DNA damage may

reduce tumor incidence. This has led to the hypothesis that the risk of cancer may be decreased by reducing DNA damage (Poirier, 2012). During this process, cells may modify their chromatin structure around the damaged DNA using epigenetic mechanisms. This means that cancer risk is not solely determined by DNA damage, but also by how the cell responds to the damage. If these changes are misregulated, they can alter gene expression in harmful ways.

The mammary tissue has a higher chance for DNA damage due to the multiple remodelings that occur throughout a woman's lifetime. Mammary glands undergo proliferation, apoptosis, and differentiation at a higher rate than most tissues in the body, making it more susceptible to problems within the DNA structure and function (Davis & Lin, 2011). Because mammary tissue is already more vulnerable to DNA damage, harmful exposures during fetal growth can increase this risk, potentially leading to long-term epigenetic changes that result in higher breast cancer susceptibility for multiple generations.

The Developmental Origins of Health and Disease Theory

Developmental Origins of Health and Disease (DOHaD) explains that exposure to environmental factors during developmental periods such as the utero, will have a long-lasting impact on an individual's health (Figure 1). The fetus relies on nutrients and hormonal signals from its mother for growth. The fetus then adapts to the signals, which help its survival after birth. Changes in metabolism may result if these early adaptations are wrong, leading to diseases that can be passed down through future generations. This disease may only appear later in life when the individual is exposed to certain environmental factors, such as having a poor diet or a lack of exercise. Factors such as maternal nutrition or stress can alter the development of the fetus through epigenetics (Lacagnina, 2019). A study showed that when a mother does not eat enough protein during pregnancy and lactation, it can lead to low initial birth weight of the offspring and a fast growth after birth. Birth weight is a good indicator of the quality of intrauterine growth which is associated with a woman's risk of developing breast cancer. If the child eats a high-calorie diet as an adult, they may be more susceptible to breast cancer due to the mother's actions during significant developmental periods (Fenton & Birnbaum, 2015). These changes can affect gene expression, increasing susceptibility to breast cancer.

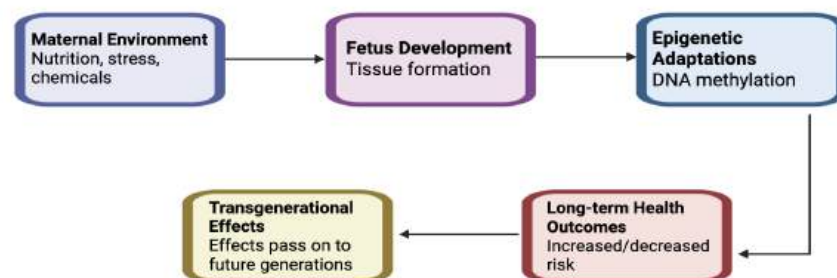


Figure 1: Developmental Origins of Health and Disease Model. (Davis & Lin, 2011)

Estradiol, a type of estrogen that is crucial in the development of breasts, can also be linked to breast cancer susceptibility. A study using rodent models found that the consumption of N-6 polyunsaturated fatty acids (N-6 PUFAs) by mothers during pregnancy increased estradiol levels. The study found that increased exposure to estradiol levels due to a high diet in polyunsaturated fatty acids increased breast cancer risk (Hilakivi-Clarke et al., 1997). Elevated estradiol during critical developmental periods can alter the programming of mammary gland tissue, making it more sensitive to hormonal signaling later in life. This intensified sensitivity may increase the chance of abnormal cell growth in offspring, leading to a greater chance of breast cancer.

Environmental Exposures and Epigenetic Risk Factors

Exposure to certain environments has a link to the development of breast cancer. However, it may take decades after exposure for breast cancer to be detected, possibly due to the latency period—the period between initial exposure and the development of a condition. Exposure to certain chemicals is a common factor in developing breast cancer, a major chemical being Bisphenol A (BPA). BPA—an endocrine-disrupting chemical—is commonly used in epoxy resins for toys, food containers, and baby bottles, among other products. BPA alters DNA methylation patterns which are crucial for regulating gene expression (Cheong et al., 2018). It has been found that BPA has the most significant effects in utero or early childhood when epigenetic programming is still being established. These changes can continue through the individual's life. Low levels of BPA have been found in 93% of urine samples taken in the United States, showing an extensive exposure to the chemical. Studies on animals have found that even low levels of BPA may affect the development of mammary glands, meaning that even exposure to low levels of BPA may result in changes such as hormone sensitivity that lead to the development of breast cancer later in life (Muñoz-de-Toro et al., 2005).

Research has shown that chemical and hormonal exposures can develop epigenetic changes in mammary cells. A human cell model was created where breast progenitor cells—a type of cell in the mammary gland—were exposed to chemicals and then left alone. It was discovered that the cells that lived longer were more vulnerable to damage, which could be passed down along generations through epigenetics (Humphrey et al., 2019). Past research also shows that exposure to hormones such as E2 and DES can cause gene changes linked to breast cancer. The study found that long-term BPA exposure led to estrogen receptor α (ER α) signaling and changing the gene expression in the offspring's cell. These similar gene changes were found in ER α positive breast tumors, showing that epigenetic changes can be passed down.

Heavy metals are also suspected to have an impact on the development of breast cancer. Individuals may be exposed to heavy metals from their diet or drinking water. The International Agency for Research on Cancer identifies arsenic, cadmium, nickel, and aluminum as Group 1 human carcinogens—known substances that can cause cancer in humans (Lequy et al., 2023). A case study was conducted to find that exposure to inorganic arsenic was linked to an increased risk of breast cancer (López-Carrillo et al., 2020).

Effects of epigenetic changes throughout generations

Epigenetic changes due to environmental exposures can have transgenerational effects on breast cancer. This means that exposure to environmental factors, such as BPA, in one generation can lead to altered gene expression in the offspring, even if they are not directly exposed (Figure 2). When these changes are passed down, they affect how genes linked to breast development are expressed. In breast cancer specifically, inherited epigenetic changes may impact the genes involved in DNA repair and cell cycle control, increasing the risk of cancer in future generations. Animal studies have shown that maternal exposure to BPA leads to changes in the mammary gland development, increasing cancer susceptibility in second and third generations (Manikkam et al., 2013).

In addition, paternal factors can also affect the chance of breast cancer in offspring. Poor nutrition before birth can harm a male's sperm, leading to an increased risk of epigenetic disease. An experiment using mice found that malnutrition in the father reduces the weight of the daughters at birth, which leads to reprogramming of the mammary tissue and tumors. It was also found that daughters of fathers with low protein have higher rates of mammary cancer and tumors will be found earlier (Santana da Cruz et al., 2018). This indicates that the father's diet can influence not only fetal growth, but also long-term breast cancer susceptibility in offspring. These findings show that epigenetic inheritance is not limited to maternal exposures, but also paternal diet and health prior to conception.

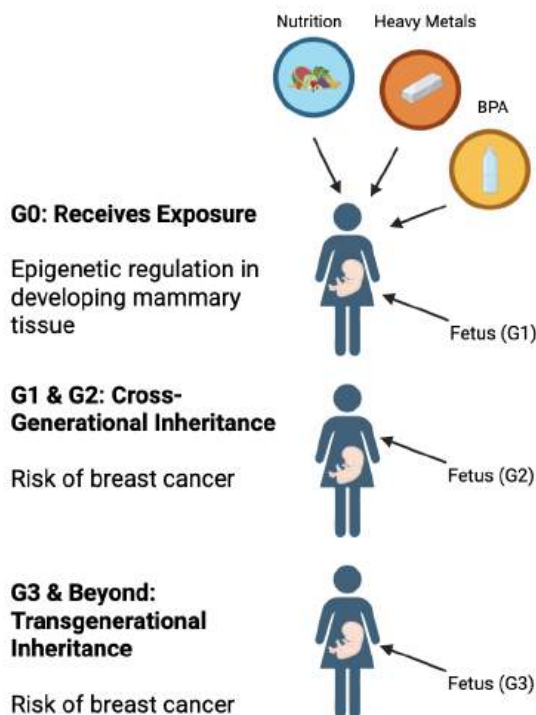


Figure 2: Effects of Environmental Exposures on Breast Cancer Susceptibility throughout Generations. When a mother is exposed to environmental exposures during pregnancy, the offspring's mammary tissue may be affected. These effects can be passed down through generations that were not directly exposed, increasing the chance of breast cancer (Sonata da Cruz et al., 2020).

Conclusion and future studies

Breast cancer remains one of the most common diseases worldwide. While genetic mutations can contribute to the susceptibility of breast cancer, many cases are a result of epigenetic changes. These changes are influenced by factors such as environmental toxins and nutrition. During the period of fetal development, the offspring is more vulnerable to establishing long-lasting epigenetic changes that may increase their risk of breast cancer. On top of this, misregulated responses to DNA damage can create environments for tumor growth. Since these epigenetic changes can be passed down through multiple generations, it is essential to understand the details of their causes.

Additional research can be done on whether exposure amounts to various environmental toxins will increase breast cancer susceptibility. Understanding whether there is a limit to exposure amounts is critical for shaping safety guidelines and public health regulations. Since environmental toxins can influence breast cancer risk through epigenetic modifications, studying different exposure levels can reveal how epigenetic mechanisms respond to varying doses. By identifying these risks, researchers can determine which populations are at a higher risk of developing breast cancer.

By gaining a better understanding of epigenetics in breast cancer, improved prevention and early detection techniques can be implemented. Since epigenetic changes can be reversed, this knowledge allows for the development of new therapies that could correct harmful epigenetic modifications.

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Dancing Toward Development: A Review of the Effects of Dance on Adolescent Cognitive, Mental, and Academic Outcomes By Shirina Cao

Abstract

Dance is regarded as an effective extracurricular activity to produce both physiological and psychological benefits, especially during the later childhood and adolescence period. This study explores the benefits of dance on mental health as well as cognition and academics, two developmental factors that receive less attention in adolescent literature, and discusses the combined effects of the three together. Eleven articles were analyzed for this literature review. Although dance intervention type and length varied across studies, common themes suggest that dance as a recreational activity produces numerous mental, cognitive, and academic benefits such as self-esteem and emotional regulation, memory capacity, and motivation in school. Given these results, schools are encouraged to include dance into their curriculum. Additional research that further explores dance as an extracurricular would be beneficial.

Keywords

Recreational dance boosts self-esteem, Emotional regulation, Memory capacity, Academic motivation for older children and adolescents globally.

Introduction

The arts have become an increasingly prominent topic of interest in health research due to their well-established benefits for enhancing quality of life (Chappell et al., 2021). Among the many art forms, dance, which is defined as a social movement that requires individuals to listen to music and keep in time with others (Quiroga Murcia et al., 2010), offers a multidimensional practice blending physical movement with artful expression. This review focuses on dance styles that evoke creative movement or social bonding and dancing as a form of recreation. Dance can strengthen bonds and create a community, thereby improving psychosocial well-being and emotion regulation, and promoting brain health (Chappell et al., 2021; Quiroga Murcia et al., 2010; Tao et al., 2022). While these benefits can significantly enhance individuals' lives across the lifespan, research suggests they are especially valuable during later childhood and adolescence (Tomescu et al., 2023).

This review focuses on older children and adolescents ages 6-18. Childhood is typically defined as people under the age of 18 (Anderson et al., 2003). Childhood is a vulnerable period, which establishes a critical foundation for future academic success, health, and general well-being. Indeed, any negative experiences during childhood can hinder cognitive, intellectual, and rational development (Anderson et al., 2003; Tao et al., 2022). Given that participating in grade school during this age adds additional social and academic burdens, dance can serve as an effective outlet to mitigate these negative experiences that can serve to benefit students if implemented therapeutically within schools (Liu et al., 2022). Studies show that dance can improve self-identity and body image, relieve anxiety or aggression, and induce happiness (Tao

et al., 2022). Many studies focus on the benefits of dance on mental health and physical health, but focus less on cognition and academic performance, highlighting important areas of research that warrant further investigation.

This review will summarize the positive effects of dance on adolescent mental health, cognitive development, and academic achievement. By examining findings from recent studies, this paper aims to better understand how dance promotes psychological growth for adolescents and its positive impacts emphasize why dance should be included in school curriculums.

Methods

Two online databases (PubMed and Google Scholar) were used to search for articles over the course of June and July 2025. The following search terms were used: “dance effect on adolescent cognitive development,” “recreational dance effect on adolescent psychology,” “dance effect on adolescent cognitive development,” “recreational dance effect on adolescent memory,” and “dance academic achievement.” The inclusion criteria for selecting appropriate articles included the following: peer-reviewed manuscripts, participants ages 6-18 who were neurotypical, a primary focus on dance and mental health, cognitive development, academic achievement, or a combination of these areas, and publication dates within the last 20 years (2005-2025). Exclusion criteria included dance movement therapy studies, because they do not align with the focus of this review on creative and collaborative dance. Of all articles yielded from the initial search, the 11 most relevant articles were chosen and grouped by theme: 1) mental health, 2) cognitive development, or 3) academic achievement, with four articles in each group, to synthesize current research.

A comprehensive review was completed to include: number of research subjects, age of research subjects, country of research, researched dance style, length and duration and frequency of intervention, and overall findings. These details help with analyzing effects across studies, as differences in duration or type of dance can produce different results, and future research can imitate the same research process. See Table 1 for a more concise overview.

Table 1: Research studies included in this review

Theme	Author(s)	Population	Intervention	Focus	Results
Mental Health	Enloe et al. (2025)	Ages: 11-14 N = 23 Female	Hip Hop dance 75 minutes Twice a week 8 weeks	Self-esteem, body image, mindfulness, and well being	Participants reported greater levels of self-esteem, positive body image, and mindfulness in surveys after the hip hop dance intervention compared to before.
Mental Health	Duberg et al. (2020)	Ages: 13-18 N = 112 Female	Spontaneous movement dance vs do-nothing control group	Physical and emotional symptoms of stress	Participants in the experimental group reported a decrease in physical discomfort and emotional distress caused by stress in surveys compared to the control group.

			75 minutes Twice a week 8 months		
Mental Health	Liu et al. (2022)	Ages: 14-18	Literature review	Emotional regulation	Found a positive relationship between dance, emotional regulation, and overall mental health and well-being.
Mental Health	Stutesman et al. (2025)	Ages: 7-12 children + parents and instructors N = 65	Choice of dance class Qualitative review	Physical and psychological well-being	Dancers and parents reported improvement in mental health and teachers attested that teaching methods can help or hinder well-being.
Cognitive Development	Oppici et al. (2020)	Ages: 8-10 N = 75	High-cognitive and low-cognitive challenge groups learning jazz choreography Vs regular PE class control group 60 minutes Twice a week 7 weeks	Teaching styles affecting cognitive development for dancers	The high-cognitive challenge group had significantly improved memory capacity, while the other two groups did not.
Cognitive Development	Tudor et al. (2024)	Ages: 11-13 N = 12	Qualitative review on existing street dancers	Relationships between working memory, perceived stress, and technical abilities	Found correlations that dancers with higher levels of perceived stress had better memory and dancers with higher levels of memory had better technical skills.
Cognitive Development	López-Serrano et al. (2017)	Ages: 6-18 N = 273	Literature review	Effect of Dance Dance Revolution on cognitive and academic	Individuals who played exergaming machines had higher executive function compared to those resting

				performance	
Cognitive Development	Rutkauskaitė et al. (2025)	Ages: 13-15 N = 63	Just Dance vs functional training >3 times a week 30 minutes	Dance exergaming (Just Dance) effect on cognitive skills	The experimental group had larger improvement in reaction time and executive function, but no improvement in short-term memory.
Cognitive Development	van den Berg et al. (2019)	Ages: 9-12 N = 510	Just Dance videos 10 minutes Every day 9 weeks	Cognitive performance and aerobic fitness	Found no effect on cognitive ability or aerobic fitness because of short intervention duration.
Academic Achievement	López-Serrano et al. (2017)	Ages: 6-18 N = 273	Literature review	Effect of Dance Dance Revolution on cognitive and academic performance	Increased writing quality, math skills, and foreign language acquisition.
Academic Achievement	Tomescu et al. (2023)	Ages: 11-12 N = 30	Dance sport 60 minutes Twice a week 6 months	Impact of dance sport on children's learning	Found greatest improvements in test-taking, concentration, and academic motivation.
Academic Achievement	Zhou et al. (2023)	Ages: 10-12 N = 305	Latino dance 120 minutes Twice a week 28 months	Latino dance lessons improving left-behind children's academic self-efficacy	Latino dance interventions improved LBC students' general self-efficacy, academic-efficacy, and self esteem to improve their academic performance.

Results

Mental Health

Mental health is “a state of well-being in which the individual realizes his or her own abilities, can cope with the normal stresses of life, work productively and fruitfully, and make a contribution to his or her community” (Galderisi et al., 2015). Across the articles focusing on

dance and adolescent mental health, studies evaluated the extent to which dance can improve mental health, with a particular focus on self-awareness and anxiety.

Enloe et al. (2025) ran a research study involving 23 girls aged 11 to 13 from the southeastern United States, and participants completed surveys before and after participating in a hip hop dance intervention. The duration of the intervention was eight weeks, consisting of two classes per week for 75 minutes. Participants were measured on their mental health to determine the benefits of dance on self-esteem, body image, mindfulness, and well being. Comparisons between the pre- and post-intervention surveys found that participating in hip hop dance classes led some individuals to report lower levels of anxiety about their bodies, higher self worth, and greater self-awareness. The authors postulated that the observed decrease in anxiety after the hip hop intervention may be attributable to increased familiarity with dance due to accumulated experience with the artform, thus reducing worries of judgement and enhancing self-esteem. However, the authors noted that fluctuations in feeling states are common among this age group, such that participants may report improvement one day, then report regression another day. This limits the accuracy of self-reported surveys within this population.

Duberg et al. (2020) from Sweden completed a randomized controlled trial (RCT) with 112 girls aged 13 to 18 to assess whether dance can effectively reduce stress. As part of their RCT, the researchers divided the 112 participants into one group that participated in a spontaneous movement dance intervention, consisting of two 75 minute dance classes per week for 8 months, and another group that did not participate in any intervention. Individuals recruited for the study previously showed physical and emotional symptoms of stress like headaches and feelings of anxiety. All participants completed surveys directly following the conclusion of the intervention, as well as 4- and 12-months post-intervention. Results showed a decrease in both physical and emotional symptoms of stress in the experimental group compared to the control group right after the intervention, but differences between the two groups became less distinguishable long-term. This suggests that dance intervention should be continued to maintain the results .

Liu et al. (2022) conducted a literature review on the effect of various styles of dance education on Chinese teenagers' emotional regulation, aged 14-18. They found multiple studies pointing to the positive relationship between dance and emotional regulation, mental health, and overall well-being, noting that the degree of benefit depended on the style of dance and type of class the teenagers engaged in. For instance, ballet and contemporary, which emphasize graceful movements, help boost adolescents' self-esteem and body image. Meanwhile, dance styles such as hip-hop allow dancers to express themselves, which improves emotional regulation and self-image, due to the improvisation style of the dance. However, these findings were not observed among other countries like Spain and Korea, indicating potential cultural influence. The review concluded that there are many nuances to dance education, and more detailed research is needed to better understand how this may vary across cultures.

Stutesman et al. conducted a qualitative review based on open-ended survey responses from 65 children ages 7-12 and their parents as well as interviews with 17 dance instructors to

explore the effects of dance on mental health in the United States. Most of the dancers participated in dance before the study, with an average of 3 years of previous experience for 1.6 hours per week, with only three having no prior dance experience. For the study, participants danced as an extracurricular outside of school for at least one hour a week for one academic year, with the study not focused on the duration and frequency of dance instruction. Participants could choose any dance style, but most participants chose ballet, modern, or jazz. After completing one year, the dancers, as well as their parents and teachers reflecting on the children's experience, reported improvement in emotional health and self-discovery through expression and building confidence. While not the primary focus of the study, teachers attested that current teaching ideologies aim to benefit dancers' well-being and thus create these positive effects, but other dance education ideologies, such as those that are authoritarian, can have consequences for well-being (Stutesman et al., 2024).

These studies revealed improvements in mental health for participants of a dance intervention, shown through decrease in stress and increase in self-esteem, self-discovery, and emotional awareness. Duberg et al.'s study and Liu et al.'s review show that dance styles focused on spontaneous movements like hip hop can improve emotion regulation and reduce stress.

Cognitive Development

Cognitive development is the growth of information processing, thinking, and reasoning, such as linguistic and problem-solving processes (Siegler, 1989). Research shows that dance, as well as other sports, can be an effective activity for fostering enhanced cognitive development like attention, perception, and decision making (Tudor et al., 2024). Given that dance requires memorization of steps and stimulates many cognitive functions, it is considered an effective strategy to engage working memory in children (Oppici et al., 2020).

Given that different kinds of teaching styles may impact the cognitive development for dancers, Oppici et al. studied 74 children ages 8-10 in Australia and their working memory capacity based on teaching pedagogies. There was a control group that took normal physical education (PE) classes with no dance education. The experimental group danced jazz choreography during their PE classes for an hour twice a week over 7 weeks, not dancing outside of class. The experimental group was further divided into two groups, labeled low-cognitive and high-cognitive challenge. Demonstrations of the choreography were more frequent in the low-cognitive challenge group rather than the high-cognitive challenge group ($p < 0.01$ in both). In the high-cognitive challenge group, instructors focused more on delivering feedback verbally to enhance attention and encourage participants to recall previously learned sequences to challenge their working memory capacity. Results found that the high-cognitive challenge group had significant improvement in their memory capacity, while the low-cognitive challenge and control group had no significant improvement (Oppici et al., 2020). This is thought to be due to the instructors offering less demonstration of the dance moves, pushing students to memorize the choreography. This indicates utilizing a high-cognitive challenge teaching approach may help dancers improve their working memory capacity.

Tudor et al. found that individuals who take part in Hip Hop Culture value freedom of expression and develop stronger resilience to hardships. As a part of Hip Hop Culture, hip hop dance or streetdancers also value this expression, and need strong memory to remember routines. The study included 12 street dancers ages 11-13 in Bucharest, Romania, on the relationships between their working memory, perceived stress, and technical abilities using the TIM computerized test to record memory, the Delphy method to test athletes' technical skills, and a Stress Perception Questionnaire. The study found that dancers with higher levels of stress had better memory capacity and dancers with higher levels of working memory scored higher on their technical skills (Tudor et al., 2024). The authors note that although causality was not determined, it is possible that perceived stress creates urgency that pushes dancers to work their memory more effectively.

López-Serrano et al., based in the United States, reviewed the study of Dance Dance Revolution and other exergaming interventions in a literature review of papers from 2007-2017, ultimately choosing 3 studies that met their criteria, totalling 273 children and adolescents aged 6-18. Exergaming is a form of video game that requires the player to be physically active. They found that individuals that used an exergaming intervention for four hours had higher executive function performance than individuals that performed sedentary activities. The authors note this finding may have been driven by increased blood flow to the cerebral cortex, which is consistent with prior studies (Chaddock et al., 2012). In a different study, teenagers 12-15 years old who played Pokemon GO for 50 minutes over six weeks increased their selective attention and concentration (López-Serrano et al., 2017). While Pokemon GO is not a dance game, dance exergaming can perhaps combine benefits from physical movement and gaming.

Rutkauskaite et al. conducted their research in Lithuania with 63 teenagers from a sports club ages 13 to 15 to participate in a control group of functional training or an experimental group with Just Dance as a video-game based dance exercise for four weeks, at least 3 times a week for 30 minutes. To measure cognitive development, participants were asked to complete the Stroop Test to measure processing speed and executive functioning (i.e., cognitive flexibility and inhibitory control); Trail-Making test Parts A and B to measure attention, motor-based processing speed, and cognitive flexibility; and Visual Digit Memory test; evaluating visual short-term memory and attention concentration. Results found that the group with Just Dance had larger improvement in cognitive performance, particularly in reaction time and executive function, while visual short-term memory did not improve as compared to those in the functional training control group (Rutkauskaite et al., 2025). The authors claim that Just Dance being a video game is more appealing to children and thus enhances the benefits. Moreover, because the game does not require players to memorize steps like a normal dance class would, players' short-term memory would not be stimulated.

In the Netherlands, van den Berg et al. studied the effect of Just Dance videos on 510 children aged 9-12 and their cognitive performance. The study assessed and compared the impact of daily 10-minute exercise breaks for 9 weeks (i.e., experimental group), an intervention feasible to practice in schools, with a no-treatment control group. The exercise breaks consisted

of 3 Just Dance videos. Van den Berg et al. tested with four cognitive tasks, but found no effect on cognitive ability, likely due to the short duration of the intervention. In previous studies on physical activity, positive effects on cognitive development were achieved long term, so authors provide the theory that longer interventions are needed to produce these results. They also suggest that the exercise breaks may have been too difficult, limiting the time participants spent active at moderate or vigorous intensity, which is the frame suggested to produce the most cognitive effects (van den Berg et al., 2019).

The studies in this section suggest improvement in two main domains of cognitive function: attention and memory. Findings suggest that development of memory is driven by teaching pathologies that encourage self-reliance in learning. Attention is enhanced by exergames that require players to focus on specific movement signals.

Academic Achievement

Academic achievement refers to the extent to which a student meets learning goals within instructional settings, demonstrated through performance across various subjects and the acquisition and understanding of new knowledge like reading comprehension, math fluency, financial and/or science literacy, problem solving, and computer knowledge (Steinmayr et al., 2014). Academic achievement can be disrupted by stress that can occur from trying to balance school with competing social demands and external distractions such as social media, and dance can teach skills such as emotional regulation to help mitigate stress or maintain focus to perform better in school (Gupta & Mili, 2017).

López-Serrano et al., based in the United States, reviewed previous studies of Dance Dance Revolution, which is a type of exergaming activity. They found that when certain types of exergaming implement augmented reality and encourage interactions between players, academic development increases for writing quality, math skills, or foreign language acquisition. The socialization aspect of exergaming also produces positive effects, as strengthening friendships can boost self-esteem or mood to conquer new challenges (López-Serrano et al., 2017), leading to higher achievement in an academic setting. The study states that exergaming machines have been implemented more in school settings, for use during free time or as an alternative choice in physical education classes.

Tomescu et al. examined the impact of dance sport on children's learning in Romania, analyzing data from 30 participants aged 11–12 using the School Motivation and Learning Strategies Inventory (SMLSI). The intervention took place over 6 months with 1 hour lessons twice a week. Dance sport, also known as competitive ballroom dancing, combines a musical ear, communication between dancers and the audience, psychomotor skills, and artistic expression. To improve children's academics, the authors recommend stimulating the learning process with multiple intelligences. These intelligences could include verbal/linguistic intelligence, explored through listening, reading, and storytelling to stimulate imagination. Another intelligence is logical/mathematical, with learning strategies from discoveries, research, and real processes. The dance intervention targeted rhythm and expression to hit different

intelligences. After the intervention, SMLSI showed the greatest improvements in test-taking, concentration, and increased motivation to perform better in school. The authors concluded that stimulating multiple intelligences through different learning strategies while practicing dance sport serves as a leisure activity that also improves school performance (Tomescu et al., 2023).

In China, Zhou et al. examined Latino dance interventions in enhancing academic self-efficacy for 305 left-behind children (LBC) aged around 10-12. LBC are children who have been left behind in rural hometowns while their parents have moved to industrial areas in search of job opportunities. Previous studies have found that LBC are more likely to drop out of school, so it is more important for them to have higher levels of academic motivation. Participants filled out the Jinks and Morgan Children's Perceived Academic Self-Efficacy Scale. Dance lessons were taught from September 2020 to January 2022 twice a week for one and a half hours each class. Results confirmed that Latino dance interventions improved LBC students' general self-efficacy, and more specifically their academic-efficacy, to improve their academic performance. Before the intervention, self-efficacy levels varied between age groups, but there was no significant difference after, suggesting that dance can help all children reach the same level, no matter how their self-efficacy was impacted by their unique home experiences (Zhou et al., 2023).

The four studies in this section support the argument that recreational dance improves academic achievement through the development of better learning strategies, improved behavior, and increased motivation.

Discussion

The studies outlined in this review suggest that dance interventions ranging from classes to exergaming can offer many benefits for adolescent mental health, cognitive development, and academic achievement. Across the studies, dance interventions appeared to not only lead to improvements in the aforementioned domains individually, but also create synergistic interactions between them to produce broader positive outcomes. For example, dance interventions can boost self-esteem to improve happiness and lead to better school performance (Zhou et al., 2023). Future research should seek to assess directional pathways among the aforementioned variables in order to determine potential mediators and moderators of such effects. Participating in dance also helps individuals develop emotional control and cognitive functions to focus attention, which can help with concentration during stressful exams (López-Serrano et al., 2017; Tomescu et al., 2023; van den Berg et al., 2019). In general, improved mental health and cognitive development correlate with higher academic achievement. Additionally, dance can produce different benefits based on gender, dance style, teaching style, and rigor. Taking into account the various strengths and limitations of this review, dance proves to be a strong potential resource for older children and adolescents overall.

Late childhood and adolescence is a time of heightened emotional sensitivity, which can result in negative outcomes such as substance abuse, self-harm, or other dangerous behaviors (Liu et al., 2022). The observed improvements in overall mental health that have been linked to

participation in dance interventions may help alleviate these negative symptoms. Recreational dance can protect against adverse mental health outcomes like anxiety and poor body image, to produce better mental health (Enloe et al., 2025). However, study findings suggest that one must continuously engage in recreational dance on a more long term basis in order to maintain benefits like lower levels of stress (Duberg et al., 2020).

Mental health benefits, such as improved self-esteem, seem to be connected to other benefits of dance, especially academic performance. Enhanced self-esteem may also help adolescents access greater motivation to engage more deeply in academics. Additionally, the emotional regulation skills that teenagers may develop through their participation in dance interventions allows students to better handle and perform under stressful situations (Tomescu et al., 2023). Tomescu et al. also found that participation in dance sport increased better emotional control in stressful situations for individuals, forming a connection between the improvement of mental health and academic achievement. Increased self-esteem allows students to be more confident in their skills and achieve better results in school (Zhou et al., 2023). Exergaming interventions like Dance Dance Revolution and dancing to Just Dance videos, respectively, also help to increase academic achievement through increasing focus and classroom motivation.

The development of executive function is an important factor for determining academic achievement (Oppici et al., 2020). Dance can stimulate cognitive development for older children and adolescents, especially in certain domains like selective attention, inhibition, working memory, and cognitive flexibility (van den Berg et al., 2019). Dance combines cognitive and motor challenges to strengthen cognitive processes with movement (Oppici et al., 2020). In the mental health regard, stress can be damaging, but Tudor et al. found correlation between higher levels of perceived stress with higher memory capacity for adolescent street dancers. This could mean that dancers can harness stress to improve their cognitive development. For adolescents who do not already have a foundation of dance, they can use dance exergaming machines like Just Dance or Dance Dance Revolution to gain similar results. López-Serrano et al. and Rutkauskaite et al. found that exergaming activities can improve cognitive functions like selective attention and concentration, but not working memory.

Dance styles which offer artistic expression through spontaneous movements, like hip hop or creative dance and improvisation, allow for greater improvements in self-expression and understanding while more precise styles like ballet boost self-esteem (Duberg et al., 2020; Enloe et al., 2025; Liu et al., 2022; Stutesman et al., 2024). Dance style influences what benefits dancers can receive from dance, and the type of instruction also plays a role (Liu et al., 2022; Stutesman et al., 2024). Classes with authoritative teaching can harm a dancer's mental health instead (Stutesman et al., 2024), which could potentially lead to more adverse effects, like loss of motivation in school (Chen, 2005). Higher cognitive challenges can enhance cognitive development, such that teaching dance with fewer demonstrations forces dancers to rely on their memory and strengthens it (Oppici et al., 2020). Interpreting these findings, dance serves as a therapeutic extracurricular activity that is helpful developmentally during this period of life.

However, recreational dance produces these positive results because of encouragement of dancers to express themselves, emotional regulator, and process their feelings (Liu et al., 2022; Stutesman et al., 2024). More rigorous forms of dance, like pursuing it professionally or preprofessionally, can actually induce more stress on dancers rather than reducing it (Stutesman et al., 2024). The heavy use of mirrors and expectations from social media can cause dancers to struggle with body image (Heiland et al., 2008), but dancing therapeutically or recreationally can help young people, both male and female, become more accepting of their bodies (Grogan et al., 2014). It would be interesting for future studies to directly compare recreational dance to professional dance, and how different aspects are affected.

There are nuances to the benefits of dance across genders, as females may benefit more from the physical activity of dance and gain better study strategies and more knowledge skills, but boys tend to have fewer anxiety symptoms and more motivation and attention concentration (Enloe et al., 2025; Tao et al., 2022; Tomescu et al., 2023). While female-specific benefits were not a focus of any specific article, some studies included only female participants, like Enloe et al. and Duberg et al., and they explore some specific benefits of dance for females. Enloe et al. suggest that dance, specifically hip hop, can encourage better behaviors in school for females, such as not following gender-role patterns of staying quiet and not utilizing teacher attention. For adolescents to participate in some form of physical activity daily is extremely important, however, a lot don't, especially females, as exercise seems to not fit the image of femininity. Dance is a good solution, as it offers the same benefits as physical exercise and is more appealing to females (Tao et al., 2022). Many sports extracurriculars offered in school cater towards males, so adding dance as an option would be beneficial for females. Future research can focus more on the differences of benefits gained by both genders through dance, as well as genderfluid individuals.

A strength of this review is it discusses findings that span across academic disciplines, including cognitive science, neuroscience, psychology, sociology, and the arts. However, there are some limitations of the studies used in this review, such as a frequent lack of definition of dance, small sample sizes, and short intervention periods in the studies assessed. Future research should clearly define the type of dance intervention and instruction and explore long-term effects of dance in interventions lasting at least 75 minutes, once a week, for greater than 5 years. Many studies included in this review describe “dance interventions” but do not explain what kind of dance is being used. Inconsistencies between studies make it difficult to decipher consistent relationships and results (van den Berg et al., 2019). When using small sample sizes, substantial results were not yielded (Enloe et al., 2025). Enloe et al. also highlighted lack of knowledge on long-term effects because of its short duration, and possible influence in participants’ answers to yield more positive results. Van den Berg et al.’s study found no patterns of cognitive improvement because of its short 10-minute intervention periods. However, experts suggest schools should include physical activities for a minimum of one and a half hours a day (Tomescu et al., 2023), and holding longer intervention periods can potentially produce more results. A limitation of this review is that due to time constraints and limited access to academic databases,

it is possible that not all relevant papers on the topic were included. Future reviews could benefit from a more comprehensive search to include additional perspectives and findings. Nonetheless, the comprehensiveness across the three topics of mental health, cognitive development, and academic achievement provide substantial information to compel educational systems to implement more dance practices.

Overall, there is strong potential for dance to be a positive resource for older children and adolescents. Given the rising rates of mental health issues and academic difficulties among children of this age (Bor et al., 2014; Tomescu et al., 2023), as well as the importance of engaging in activities that further enhance their neurodevelopment, it is critical for school systems to consider dance as a helpful intervention to mitigate these issues. Adolescents need to have some physical activity every day, however, around 89% of activities in school curriculums are sedentary (Tomescu et al., 2023). Dance is a good solution, as it offers the same benefits as physical exercise and also involves artistic expression, supporting health and well-being in meaningful ways (Chappell et al., 2021). Adding dance into the school curriculum allows for more nuanced physical movement that promotes healthier bodies and lifestyles. Offering hip hop or creative dance in school can offer accessible ways for social connection between students and increased artistic expression, encouraging self-discovery and relief from stress. However, even something as simple as an exergaming machine like Just Dance for students to use during break times can produce these benefits. Educators and policy makers should consider additional funding for including dance into school curriculums to foster environments in which adolescents can thrive.

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