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Addressing Hypertension in Rural South Asia: Socioeconomic Determinants and Policy Solutions By Rimsha Faheem

Abstract

Throughout rural South Asia, hypertension has become a significant public health concern. Hypertension, related to high blood pressure, is a medical condition which relatively increases the risk of heart disease and other life threatening health problems. This paper explores in which ways hypertension is prevalent in rural South Asia through exploring socioeconomic and cultural factors that influence the condition and through the discussion of disease management. These problems include challenges surrounding the poor health infrastructure, lack of awareness, and lifestyle choices that allow for hypertension to increase. By looking into these factors, this research paper aims to provide valuable insight to create targeted interventions and policies that will effectively reduce hypertension in rural South Asia. A clear understanding of disease factors will allow for the development and progress of public health policies through resource access improvement and promotion of healthier community lifestyles. Ultimately, this study aims to support ongoing efforts to reduce hypertension and its related health risks in rural South Asia.

Introduction

Hypertension is a health problem that affects an estimated 1.13 billion people worldwide, and this number is expected to continue increasing, especially in low and middle-income countries (Jafar et al., 2018). Hypertension is when the blood pressure found in a human's blood vessels is constantly at a high rate. This causes serious health problems that directly affect the cardiovascular system and can cause various diseases such as heart attacks and strokes. Hypertension is known to be a leading cause of premature death worldwide (Mills et al., 2020). The situation is especially critical in rural South Asia because it covers several number of unique challenges, including poor access to health, poor infrastructure, and very low levels of public awareness (Rahut et al., 2023). Such factors make timely diagnoses and proper treatment a big challenge, hence predisposing citizens to many undiagnosed cases and eventual preventable health complications. Healthcare challenges in rural South Asia are compounded by socio-economic and cultural factors that affect hypertension management. There is an overriding issue of poverty; many rural individuals might not afford routine doctor check-ups or the medications that are part of hypertension control. Low-income groups are more unlikely to seek medical care and tend to delay treatment until hypertension manifests in severe health complications (Chaturvedi et al., 2023). Cultural beliefs and practices also play an essential important role in determining health outcomes. In rural settings, hypertension usually goes unnoticed or gets subdued because it rarely presents immediate symptoms (Kalyani et al., 2020). Many, therefore, might not seek medical attention until their conditions worsen. The prevalence of hypertension in rural South Asia is alarmingly high. In India, nearly 25% of rural adults have hypertension, yet fewer than half of them are aware of it, and even fewer receive the necessary treatment (Farrukh et al., 2022). Similar trends are seen in rural Pakistan and Bangladesh, where

hypertension is widely underdiagnosed, which can lead to dangerous conditions, such as heart disease or kidney failure (Farrukh et al., 2022). Besides, cultural stigma associated with chronic conditions such as hypertension may prevent people from seeking medical care or even publicly discussing their health status. The interaction of these factors based on culture, in combination with a lack of health awareness, forms the high levels of undiagnosed hypertension that characterize rural South Asia.

There is a significant gap in research studies and healthcare interventions related to the management of hypertension in rural South Asia. Most of the reviewed studies involve populations in urban areas, while rural settings remain underrepresented. Further, few studies have evaluated the efficiency of culturally adapted interventions in rural settings. This paper will examine the causes of the high prevalence of hypertension in rural South Asia, emphasizing socioeconomic, cultural, and healthcare challenges. Therefore, The study seeks to highlight some loopholes in the current interventions carried out and use those opportunities to recommend strategies for enhancing hypertension management in these resource-scarce communities.

The current study hopes to contribute to a better understanding of the challenges posed by hypertension management in rural South Asia and to suggest recommendations toward more effective and culturally appropriate healthcare solutions.

Biology of Hypertension

Hypertension, which refers to high blood pressure, is a medical condition that affects the body's cardiovascular and renal systems, specifically the body's blood vessels, heart, and kidneys. Regular blood pressure should be measured at around 120 over 80 millimeters of mercury or 120/80 mm Hg (Riley et al., 2018). The first number represents the systolic pressure, which is the force of the blood flow when blood is pumped out of the heart, and the second number is the diastolic pressure, which is measured between heartbeats when the heart is filling with blood (Arackal & Alsayouri, 2023). For those who suffer from hypertension, blood pressures can measure 130/80 mm Hg or more (Riley et al., 2018). This is extremely dangerous as it majorly impacts the heart, blood vessels, and kidney systems if left untreated.

Hypertension significantly impacts the heart which is a vital organ that the human body needs in order to function properly. Hypertension forces the cardiac muscles to exert more energy into pumping blood through blood vessels that become more constricted and less elastic due to high blood pressure (Magder, 2018, 2024). Hypertension is also a leading factor for coronary artery disease, which is a condition that slows down blood flow to the heart and increases the risk of sudden heart attacks because it creates a buildup of plaque in the arteries (Baby, 2023). Individuals who suffer from hypertension are 3 to 4 times more likely to develop heart disease compared to those with normal blood pressure (Fuchs & Whelton, 2020). Along with the heart, the blood vessels are also severely affected. The blood vessels become prone to narrowing, which reduces their ability to dilate and leads to vascular remodeling (Zeng & Yang, 2024). This process increases the risk of aneurysms which can rupture and cause life-threatening complications such as strokes. Additionally, hypertension is a leading cause of chronic kidney

disease, which can lead to kidney failure and end-stage renal disease, which may require dialysis or a kidney transplant (Evans et al., 2022). The small blood vessels in the kidneys become damaged over time which restricts their ability to filter waste products from the blood and maintain a balance of fluids within the body.

A combination of genetic and environmental factors causes hypertension. An adult who suffers from high blood pressure carries the ability to pass their gene to an offspring, which may cause them to deal with hypertension or increase their risk of developing it (Goodwin & Roland, 2022). Lifestyle related factors also play a role in the development of high blood pressure levels. This is regarding a person's food habits, weight, attention to physical activity, and even alcohol intake (Liangpunsakul et al., 2010). For example, when people have high sodium diets, it can increase their likelihood of raising their blood pressure (Carey et al., 2018). In addition, weight has also been shown to significantly impact blood pressure. When people reach levels of obesity within their weight, it puts a lot of force on the cardiovascular system and increases the blood volume which can eventually lead to hypertension (Shariq & McKenzie, 2020). These are examples of factors that cause hypertension in families even when it is not passed down genetically. This disease can be passed down by family genetics or shared family lifestyle choices.

This chronic condition is often referred to as a "silent killer" within the body. Hypertension's symptoms are unrecognizable until the blood pressure levels become significantly high and life-threatening which require immediate medical attention. Some of these symptoms and indications of extremely high blood pressure levels include headaches, dizziness, blurred vision, shortness of breath, and chest pain (Robinson, 1969). When looking at this problem statistically, over one billion people suffer from hypertension worldwide, and still fewer than 20% have their condition under control due to a lack of regular monitoring (Mills, Stefanescu, & He, 2020). Another biological fact about hypertension is that it affects men more than women. Although a higher proportion of men overall have high blood pressure, 51% of men and 40% of women, hypertension rates are higher among women than men after age 60 (Szabo, 2024). Menopause is when a woman of older age, usually around 50-60, experiences hormonal changes in their body that affect their mood, body, and health. Hypertension is responsible for approximately 45% of all cardiovascular-related deaths (Wu et al., 2015). This represents how serious of an issue hypertension is and how it globally affects people of all genders and ages.

Hypertension is a condition caused by multiple factors that affect the heart, blood vessels, and kidneys. This often leads to severe complications like heart disease, stroke, and kidney failure. The causes of genetic, environmental, and lifestyle factors contribute to its development, and its asymptomatic nature makes regular monitoring a necessity for early detection and treatment. Without proper management, hypertension can lead to life-threatening conditions, emphasizing the need for prevention and early intervention.

Treatments of Hypertension

Hypertension can do severe damage to the cardiovascular systems within the body, and it is essential that people find ways to get treated before their conditions worsen. To reduce the effects or get rid of hypertension, medical professionals recommend a combination of pharmaceutical medications, lifestyle changes, alternative therapies, and newer experimental treatments.

A standard method for treating high blood pressure is using pharmaceutical medications. The medications work by easing the narrowed blood vessels or removing excess salt and fluid within the body (Al-Makki et al., 2022). An example of this type of pill is known as a diuretic, or “water pill”, and this medicine is prescribed to help lower blood pressure. Another example of a common medication is Angiotensin-Converting Enzyme inhibitors, such as lisinopril, which help reduce the body’s blood pressure by blocking certain hormones (Al-Makki et al., 2022). Calcium Channel Blockers also work by blocking calcium from entering the blood vessels and heart cells (Al-Makki et al., 2022). In extreme cases, patients are also prescribed more severe medications that interfere with the bodily systems more. This can include Beta-blockers to reduce the effects of heart disease and prevent heart attacks (Watson et al., 2024). Hypertension patients may require multiple forms of medication depending on their condition. These medications are accessible through proper pharmacies, so not every country would have access to such resources.

While medication is a common application to managing high blood pressure, there are also lifestyle changes that people can take to reduce the chances of increasing their blood pressure levels. What a person eats and their daily diet is a huge part of managing hypertension. One way people use this fact about hypertension is by following a Dietary Approach to Stop Hypertension, or “DASH diet,” to reduce their sodium intake or other dietary factors that can increase blood pressure within the body (Filippou et al., 2020). A meta-analysis found that the DASH diet can reduce blood pressure to 4.4-7.4 mm Hg (Filippou et al., 2020). This decrease is likely an effect of a reduced intake of salt. Another critical change people make in their lifestyle would be the inclusion of physical activity that exerts the body and keeps the heart pumping. These forms of exercise help the heart become stronger and function better. This can naturally lower blood pressure as the heart would start using less energy to pump blood through the cardiovascular system. Exercise lowers blood pressure by helping the heart and by helping maintain and manage body weight and fat. Even losing 5 to 10% of one’s body fat can significantly lower blood pressure (Ryan & Yockey, 2017). While keeping the physical body healthy, it is essential for patients to keep their bodies mentally healthy as well. Activities that help reduce stress include yoga, breathing, and meditation. Studies show that reduced bodily stress is directly linked to lower blood pressure (Ayada et al., 2015). Managing stress is an essential factor for controlling hypertension.

Along with medications and making holistic lifestyle changes, people use alternative therapies to help control their blood pressure levels. Some of these different therapies do not use scientifically proven practices, but people do them to practice health and provide additional support for hypertension control. For example, these treatments include acupuncture and the use of herbal supplements. All of these methods are meant for people who want at home remedies

for the problem of hypertension. People may even do this if they have regular blood pressures and want to completely avoid the risks that come with hypertension.

Recently, there has been much research into various new and experimental treatments for hypertension, particularly for those in whom blood pressure remains high even with medication. One approach that shows promise is the use of baroreceptor activation therapy. This involves implanting a device that activates the neck baroreceptors to help manage blood pressure (Iliescu et al., 2014). Early studies have shown this treatment may be helpful for those with difficult-to-treat hypertension. Another emerging treatment is renal denervation (Gupta, 2024). This minimally invasive procedure uses a catheter that sends electrical pulses into the kidneys to reduce nerve traffic critical in raising blood pressure. Though still experimental, this does show promise for certain patients with resistant hypertension. Gene therapy, including other advanced techniques for manipulating high blood pressure genes, is also an ongoing study area. Researchers are looking into how gene editing could fix some of the genetic factors contributing to high blood pressure, though this is still in the early stages (Masi et al., 2024). Overall, rural South Asia carries such treatments within their communities. Still, there are a lot of inequalities and a lack of sound political and economic systems that help citizens get the proper hypertension treatment they may need (Jafar et al, 2018).

Managing hypertension involves a variety of approaches, including pharmaceutical treatments, lifestyle changes, alternative therapies, and new experimental treatments. Medications like diuretics, ACE inhibitors, and calcium channel blockers are commonly prescribed to help control blood pressure. Additionally, adopting a healthy diet, regular exercise, and stress management techniques can make a big difference. Alternative therapies like acupuncture and yoga can provide additional support, while new treatments like baroreceptor activation therapy and renal denervation offer hope for people with hard-to-treat hypertension. By combining these different methods, individuals with hypertension can better manage their condition and reduce the risks of serious health problems.

Socioeconomic Factors of Hypertension in Rural South Asia

Hypertension is a leading attributable risk factor for mortality in South Asia (Yip et al., 2014). While hypertension remains a significant health risk globally, rural South Asia significantly struggles with hypertension as a disease and is unable to take preventive measures due to their lack of access to proper healthcare systems. South Asia is significantly rural (73% Bangladesh, 64% Pakistan, 71% India, 85% Sri Lanka), and the healthcare infrastructures and providers are significantly less professional than other urban settings (Jafar et al., 2018).

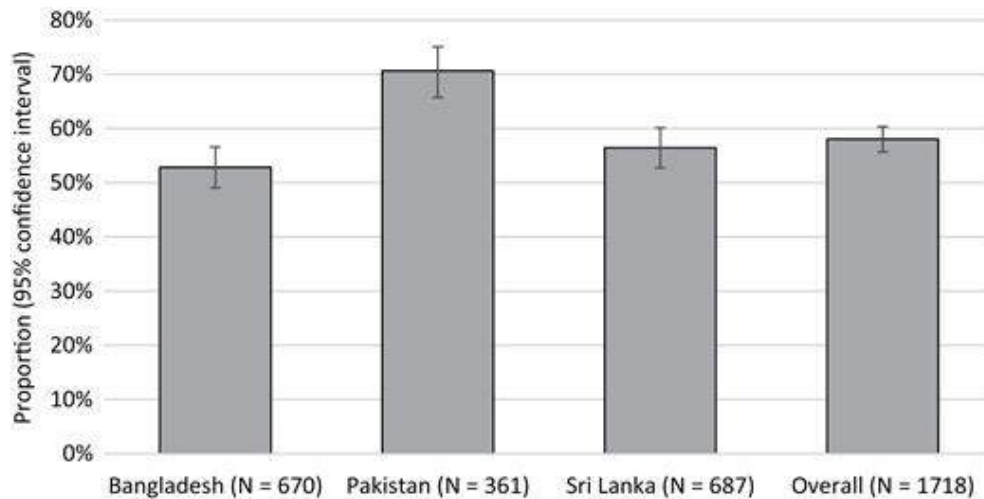


Fig 1: Proportion of individuals with uncontrolled blood pressure in South Asian countries (Jafar et al., 2018)

These statistics represent how over half of these countries have rural areas, yet many resources are still more local to the urban areas. This is only one example of the issues that play a role in the increased amount of hypertension in rural South Asia. The prevalence of prehypertension and hypertension among adults (18-49 years) is 43.2% and 14.9% in India, 35.1% and 19.8% in Bangladesh, and 25.2% and 13.8% in Nepal, respectively (Rahut et al., 2023). Adults are highly prone to hypertension globally, but a majority of these adults come from South Asian backgrounds, therefore making them more likely to be diagnosed with this disease. The three major causes for the prevalence of hypertension in rural South Asia are the lack of financial stability, proper healthcare infrastructures, and sodium literacy.

Economic factors are a significant reason why hypertension is so common in rural South Asia, as many people struggle to afford healthcare, healthy food, and lifestyle changes needed to prevent or manage the condition. Compared to urban areas where wealthier people reside, rural locations in Asia are known to have less access to resources and adequate healthcare systems. This lack of access to affordable healthcare systems is problematic because it limits access to medications and treatments for hypertension and contributes to a lack of knowledge and instruction regarding appropriate health check-ups. For example, in Pakistan and Bangladesh, the use of antihypertensive medications is extremely low due to the lack of universal health coverage and the high out-of-pocket costs, with more than 80% of medication expenses being paid by individuals (Jafar et al., 2018). This exemplifies how the high costs of medical treatments due to health care systems not being adequately established allow for poor individuals living in rural areas to have less access to treatment for hypertension. This makes it a significant concern because without proper treatment, citizens will continue to suffer from uncontrolled blood pressure and this can lead to higher mortality rates within these villages. While there are ways to make blood pressure reduction treatments more affordable, rural South Asian healthcare systems

are lacking in establishing such programs (Jafar et al., 2020). In countries like Pakistan and Bangladesh, the absence of universal health coverage and the reliance on out-of-pocket payments reduce access to proper treatment, leading to high rates of uncontrolled hypertension in these rural populations (Thippaiah et al., 2022). This portrays how economic issues in rural villages allow for hypertension to go untreated.

The lack of infrastructure in rural healthcare systems makes it even more difficult for health care providers to establish cost-efficient ways to help treat patients with hypertension. Access to healthcare services remains a significant challenge, contributing to high rates of uncontrolled hypertension. The limited availability of essential services, such as regular blood pressure monitoring, specialized care, and access to medications, contributes to the high rates of uncontrolled hypertension in these regions (Fang et al., 2017). A study examining rural communities in Bangladesh, Pakistan, and Sri Lanka found that inadequate healthcare infrastructure and limited access to essential medications were key factors in the poor management of hypertension (Thippaiah et al., 2022). There is a significant lack of healthcare technologies, such as electronic health records or telemedicine, making it difficult for patients to receive adequate treatments (Aldosari et al., 2023). Overall, these rural locations across South Asia have limited access to healthcare technologies, and healthcare infrastructures are unable to provide affordable hypertension treatments, which makes hypertension an increased issue.

Additionally, because of minimal nutrition education, many people within these regions have a very small understanding of how sodium contributes to the development of high blood pressure. A South Asian study found that the rural population consumed a high quantity of salt, unaware of its detrimental impacts on health (Rahut et al., 2023). In fact, literacy about sodium is practically non-existent in most communities; people do not even know how much salt is consumed in everyday food or how that leads to hypertension (Kalra et al., 2023). Low overall health literacy adds to this lack of knowledge, making rural populations more vulnerable to chronic conditions like hypertension, wherein they cannot make informed dietary choices. Without improvement in education about nutrition and health, these problems will worsen.

Nutrition plays a central role in managing hypertension, especially regarding salt intake. In South Asia, excessive salt consumption is one of the most significant issues, as average daily intake levels are roughly twice the World Health Organization's recommended limit of 5 grams (Ghimire et al., 2021). In South Asia, the average salt intake ranges from 10 grams per day, mostly from adding salt in cooking or when eating at the table (Ghimire et al., 2021). This is an excessive amount of sodium, which plays a significant role in the growing prevalence of hypertension because too much salt can elevate blood pressure over time. Unfortunately, most subjects living in rural South Asia are unaware of the risks of excessive salt consumption, and healthy food is not easily accessible (Kalra et al., 2023). Even though strategies for reducing salt intake have been recommended, no proper policy or program supports healthy eating behavior. Realistically, most of them consume such hypertensive items without the knowledge of risking long-term lives.

Current Policies on Hypertension

Throughout South Asia, there are national programs across countries that are established in order to act as a source of hypertension management. Examples of this include the “National Program for Prevention and Control of Cancer, Diabetes, Cardiovascular Diseases and Stroke” that was established in India in 2010 (Thakur et al., 2020). The goal of this program was to raise awareness for hypertension by providing screenings and an initiative to improve treatment of the rural and urban parts of India (Thakur et al., 2020). Even with the program promoting educational campaigns, rural locations were unable to properly adjust to the program due to the high medication costs and limited healthcare infrastructure (Thakur et al., 2020). Sri Lanka also established a “National Strategy on Prevention and Control of Non Communicable Diseases” in 2016 which released hypertension management programs that were primarily focused on education (Talagala et al., 2024). The Sri Lankan program was extremely effective in increasing access to medications and spreading awareness about reducing sodium intake, but they failed in reaching a majority of rural areas with these programs (Talagala et al., 2024). With multiple other programs being created, there always seems to be a pattern in which rural areas had less access or less effective results in managing hypertension. This goes to show that there is a clear gap for hypertension management in rural areas of South Asia.

In an attempt to fix these gaps between rural and urban access to hypertension management, there have been case studies that examine what hypertension treatment looks like in rural South Asia or what the lack of awareness is doing. In a study done in the rural village Tamil Nadu of India, they found that even with increased awareness about hypertension, the number of people who were getting treatments were low (Fang et al., 2017). The study shows that only 40% of people who knew they had hypertension were following their treatment plans because of the poor access to healthcare facilities and medication costs (Fang et al., 2017). This is an alarmingly low number considering the dangers of hypertension. This portrays that while treatments are available, there is a lack of infrastructure in ensuring all patients are provided and educated on their necessary treatments. The Essential Health Services initiative in Bangladesh did a survey in rural Bangladesh and found that 60% of patients were aware they had hypertension but only 30% of them were being treated (Khanam et al., 2014). While educational programs are spreading in popularity, there still is a lack of access to medication and pharmaceutical treatments that the patients need. Fortunately, these programs are not completely failing for all rural villages. While a majority of rural villages do not have access to these initiatives, Sri Lanka has been increasingly bringing in better health care infrastructures in the more rural areas in hopes to manage hypertension patients (Talagala et al., 2024). Sri Lanka has been able to successfully manage hypertension in these areas through bringing in healthcare workers that actively monitor blood pressures and also ensure that patients are taking the necessary medications (Talagala et al., 2024). This has allowed for a massive improvement in some districts, but there's still a lack of consistent check-ins with a high demand for more workers.

While government-funded programs are making improvements for rural areas and helping with bringing awareness to undereducated communities in South Asia, there are still flaws within the current policies which do not allow for the programs to reach rural areas properly. Initiatives that have been successful are programs that involve blood pressure monitoring through a mobile phone application (Naik & Singh, 2021). This makes it easier since it allows monitoring to be carried out even in remote areas, which is helpful for people living in rural villages. While this has improved care for some, the app's reach is limited by low digital literacy and the lack of internet access in some rural areas (Akeroyd et al., 2015). While these innovations have been successful, there are additional challenges with medication access, with a low percentage of patients regularly taking their medication (Akeroyd et al., 2015). . Infrastructures are still unstable because the programs are unable to structure clinics in rural areas (Vaughan & Edwards, 2020). Since the clinics are long distances from places, they are less available to civilians in rural locations, which limits their treatment options.

A big barrier with establishing initiatives for hypertension management comes from the lack of trained health workers being available. In India and Bangladesh, the healthcare workers do not have the time or training to diagnose and manage hypertension patients properly (Khan et al., 2021). This means that even if people wanted to seek care, they may not get the proper treatment that they need. Grassroots interventions are very crucial in addressing hypertension in rural areas. In Bangladesh, various programs that train local volunteers to raise awareness about hypertension and support monitoring have had relative success (Khan et al., 2021). This is because the programs are at the local level and involve leaders within the community who command a certain level of respect among the people. After seeing the different results, it is clear that these programs need an increase in funding, training, and support to reach more people. There are several major factors that pose crucial barriers to the actual implementation of the hypertension management programmes in rural South Asia. Financing and infrastructure form one of the strongest barriers. These areas lack the most necessary resources to enhance hypertension treatment. While programs may exist within these regions, there is very often a manpower shortage to successfully deliver them (Khan et al., 2021). Other barriers may potentially include cultural resistance where people may have a preference for traditional remedies or are skeptical about modern medicine. However, more research is needed to analyze these influences. Overall, while policies exist throughout rural South Asia regarding hypertension management, there are significant barriers which make these villages vulnerable to the disease.

Recommendations

South Asian countries have policies set in place to manage hypertension, but many of these initiatives do not cater towards the needs of those living in rural populations. In order to ensure hypertension is being treated and managed properly in rural areas, it is necessary to make improvements and administer new policies. These are recommendations on how rural areas can achieve such improvements:

Improving Healthcare Access

As mentioned previously, the access to healthcare services can be limited for rural populations of South Asia. Healthcare centers are located far away from rural villages and a lot of these centers lack properly trained healthcare professionals to deal with hypertension management.

Recommendation: To counter this issue, South Asian governments should create mobile health clinics which will bring telemedicine services to remote areas around South Asia.

Implementing mobile health clinics will address the issue at hand because this will equip rural villages in South Asia with necessary tools and medicines to help manage hypertension which they previously did not have access to. The telemedicine services will allow rural patients to get blood pressure checks and treatments. Mobile health clinics have shown to be a good investment for places like rural southern Minnesota where implemented mobile health clinics (MHC) and created community initiatives to ensure there is no barriers with lack of technology and infrastructure. As communities and governments invested into the clinics, the more resources they were able to provide for rural areas and the more funding it received (Iqbal et al., 2021). With the effectiveness shown in rural Minnesota and other rural locations across America, similar initiatives and programs should be implemented into rural South Asia.

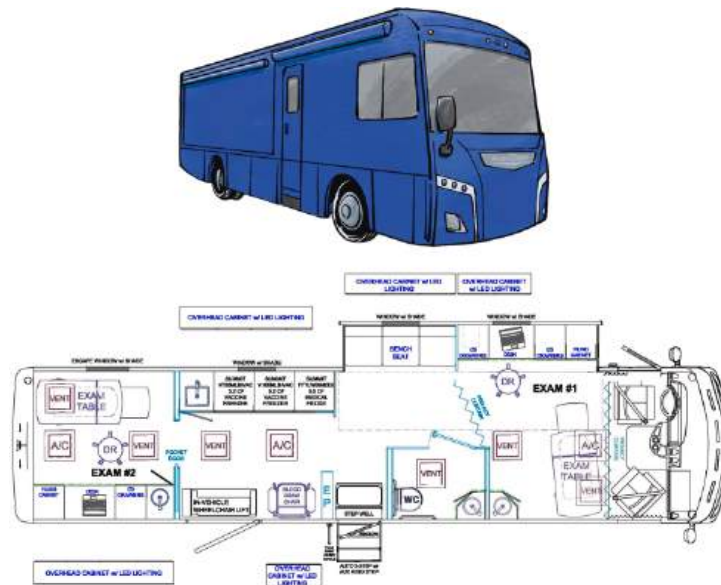


Fig 2: Graphic Representation of Mobile Health Clinic (Iqbal et al., 2022)

Implementation: Government funding should prioritize mobile clinics and telemedicine. Partnerships with local health organizations and academic institutions can train community health workers (CHWs), ensuring sustainable healthcare delivery.

Education Campaigns and Public Awareness

While educational programs have been implemented within South Asia, there is a lack of programs being targeted towards rural South Asia which makes it difficult for the population to receive proper education and get the help that they specifically need. Many people do not understand the effects of hypertension and this leads to delayed diagnosis and poor treatments.

Recommendation: To counter this issue, national medical awareness campaigns should be launched through rural South Asia through the help of media, healthcare workers, and workshops in order to increase education on hypertension management and symptoms.

Educational programs would focus on targeting younger children and young adults who can help promote public health to future and older generations who need help with managing their blood pressure. The curriculums would focus on helping people understand the complications of high blood pressure, symptoms of high blood pressure, and lifestyle choices that will help patients avoid increasing their blood pressure. Studies done in South Asia have shown that when face to face educational programs were implemented for three months there was a strong correlation between the control of blood pressure within citizens and the hypertension knowledge they were learning (Ashraf et al., 2024).

Implementation: Governments should focus on collaborating with NGOs such as the Hypertension Cardiovascular Outcome Prevention and Evidence in Asia (HOPE Asia) which are networks that aim to bring zero cardiovascular events and aim to have an ultimate decrease in hypertension deaths (Kario et al., 2019). With the help of local workshops, screenings, and collaborations with educational initiatives already in place, rural South Asia can gain access to these programs and bring in better health outcomes for the elderly and those with a family history of hypertension.

Strengthening Community Involvement in Hypertension Management

While policies that establish mobile health clinics and educational programs can be efficient, one of the most efficient ways to maintain hypertension management in rural South Asia can be seen in strengthening community initiatives because this will ensure that there is a trustworthy form of healthcare systems for people who want to take ownership of their health and personal care.

Recommendation: Rural South Asia should establish community-based hypertension management programs that are self sufficient and do not rely on the help from international and national programs which may not always cater to the needs of the local community.

Community health workers can work towards educating others in the community to help establish programs that can monitor blood pressure and basic treatment programs. These programs can then take advantage of local peer support networks and community leaders who can help motivate participation and create a proper environment to manage hypertension. Research in India shows that hypertension programs that were community-based had the most potential to provide sustained management for patients with hypertension (Om et al., 2023).

Implementation: Governments should allocate resources for training CHWs and collaborate with local organizations to sustain these programs. Peer support networks can be established through existing community structures like women's groups or religious centers.

Potential Impact

Most South Asian initiatives to control hypertension lack focus on the specific needs of rural communities. The new recommended policies are there to provide ways the government and community can take initiatives already established and cater them to the needs of the rural population. Through improving healthcare access, public education, and community involvement, the prevalence of hypertension and cardiovascular disease-related deaths can be significantly decreased in rural communities. These changes are important because it will improve health outcomes for citizens by strengthening local healthcare infrastructures and empowering communities to take control of their health. Overall, these policies will create a lasting impact on hypertension prevention and management in rural communities and across South Asia.

Discussion

The paper provides detailed information on hypertension and how it affects rural South Asian communities. Through highlighting what the disease is, its effects, and factors that make it a prevalent issue in rural South Asia, this paper clearly emphasizes how hypertension management can be improved and why it is a significant concern. Hypertension is a medical condition that keeps a patient's blood pressure high. This significantly impacts and puts strains on the vital organs of the heart, blood vessels, and kidney found in the renal and cardiovascular systems. The key risk factors of hypertension can be genetic tendencies, poor diets with high sodium, obesity, and no physical activity. This condition is prone to silently developing without noticeable symptoms, making it extremely important to have regular monitoring for detection and management.

Hypertension can be managed using pharmaceutical, holistic, and emerging approaches. With pharmaceutical management, patients are prescribed medications which target different organs of the cardiovascular system to control blood pressure. Regarding lifestyle changes, it is recommended to follow a low sodium diet, partake in daily physical activities, and start stress managing practices at home like yoga. Other alternative therapies include acupuncture and herbal supplements to provide small amounts of support in the body. An emerging approach can be seen with new therapies like baroreceptor therapy and renal denervation to create hypertension resistance.

Cultural and economic factors play a major role in the prevalence of hypertension in rural South Asia. Due to the lack of resources and financial stability in these areas, rural populations often struggle with affording healthcare services for blood pressure monitoring, prescribed medications for blood pressure control, and healthy foods that are low in sodium. These economic factors make it extremely difficult for populations to properly manage and

receive treatment for high blood pressure. From a cultural lens, rural South Asian diets are often rich in sodium, and they often lack nutritional education to spread awareness about the dangers of high sodium diets. The lack of health literacy makes rural populations more vulnerable to hypertension complications.

There are numerous policies that already exist in South Asia to manage hypertension with the aims of promoting health literacy and improving treatment quality. These programs show mixed results as urban areas often experience positive effects to these programs while rural areas do not get the necessary attention or implementation that fits their specific needs. Rural populations often face barriers of high medication costs, poor healthcare systems, and a shortage of trained healthcare workers. There have been efforts for mobile phone applications to regularly monitor blood pressure but these rural communities face challenges of limited digital literacy and poor internet access that can decrease its effectiveness for regular monitoring. There have also been prominent grassroots interventions which involve training local volunteers, but these programs can often require a lot of funding and support to reach broader populations. Overall, these solutions can be effective for rural populations if specific barriers are overcome and policies are adapted to fit their needs.

In order to improve hypertension management in rural South Asia, there is a need to implement policy changes, and these recommended changes include the implementation of mobile health clinics, national educational campaigns, and community-based hypertension management programs. If governments were to truly establish these recommendations into their policies and provide proper support and funding, these solutions would be effective. However, these policies face limitations with the high cost of mobile health clinics coming to around 650k dollars (Iqbal et al., 2021), potential internet issues, and any transportation challenges these clinics may face in rural areas. There would also be concerns over gas as it travels to remote locations. Despite these challenges, the social impact of these policies is extremely significant as it would empower communities to improve their health and take care of themselves, which will reduce hypertension and significantly decrease cardiovascular deaths. This will lead to long-term improvements of the quality of life in rural South Asia by providing communities with fundamental healthcare infrastructure and increased health literacy.

For future reference, this research paper could be significantly enhanced with more updated research and more interventions in rural South Asia. Oftentimes research provided was not recent and the interventions did not specifically target rural South Asia. If there was more provided research on what hypertension looks like in rural South Asia, it would solidify the claims made throughout the paper and show the policy effectiveness. Currently, there is a major lack of research done to improve hypertension and many initiatives focus on urban communities making it difficult to see the struggles of rural communities.

Conclusion

The research paper highlights a significant gap in hypertension management for rural populations in South Asia. The need for more policies and interventions aimed towards the needs

of these areas is emphasized as a result of this. Even though there are already national programs implemented throughout South Asia to manage hypertension, rural communities continue to face challenges and barriers that limit their access to proper healthcare and trained professionals. There are proposed solutions such as mobile health clinics, educational campaigns, and community-based programs as a way to improve health outcomes. Hypertension, being a multifactorial disease, makes management and regulation a very complex situation. The factors ranging from lifestyle habits to genetics truly make it a significant problem that must be addressed in communities that lack the health and digital literacy to understand its negative impacts. The broader implication of this research is to address these gaps as a way to reduce hypertension related deaths and cardiovascular diseases to improve the quality of life for citizens in rural South Asia.

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How Does The Brain's Perception of Episodic Memory Change Over Time?

By Arjun Balasundaram

“The Neuroscience of Learning and Memory”

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ABSTRACT

‘ Episodic memory is important and vital because it determines how someone views themselves and the world around them(Pause et al., 2013). The objective of this review was to understand how episodic memory develops over time and to determine whether there is a difference in perceiving episodic memories that changes with age. The studies selected were found on the Science Direct database, and the papers included were focused on how episodic memory develops over time for different age groups. This paper found that episodic memory improves rapidly during childhood, with structural development in early childhood, strategic developments in middle childhood, and strategic refinements and improvements in overall efficiency in adolescence, peaking with young adults, and some aspects declining with old age. This concluded that childhood is the most important time for episodic memory development. Further research needs to be done to understand how people perceive their own episodic memories, and more work needs to be done on how the perception of a memory can, if possible, be objectively rated for a more concrete approach and understanding.

INTRODUCTION

Episodic memory is the ability to recall specific events from personal experiences, or, as Allen and Fortin (2013) described it, the ability to “‘mentally time travel’ to reexperience individual events”. It is one of the primary types of memory and falls under the broader category of declarative memory. Declarative memory refers to knowledge that can be consciously recalled and expressed in words (Pause et al. 2013). It is commonly divided into two subtypes: episodic memory, which stores personal experiences tied to specific times and places, and semantic memory, which stores general facts and knowledge about the world (Pause et al. 2013).

Declarative memory itself is a branch of long-term memory, which also includes non-declarative memory. Non-declarative memory is unconscious and not easily revealed through skills and habits (Pause et al. 2013).

Episodic memory, then, is unique in that it allows us to re-experience past events vividly (Pause et al. 2013), such as the first day of school or a friend’s birthday party. However, episodic memory’s accuracy can be influenced by factors such as how much attention was paid during the original event or how much time has passed since it occurred.

The importance of studying episodic memory lies in the central role of our daily lives. A better understanding of how we recall events can have wide-ranging applications, from improving eyewitness testimony in criminal justice to enhancing learning and retention in education. Research into episodic memory also has implications for mental health. For example, knowing that memories of frightening or anxiety-provoking experiences may sometimes be

exaggerated by the brain can help individuals reinterpret those experiences in less distressing ways (Pause et al. 2013)

Beyond practical applications, episodic memory is deeply tied to how people perceive themselves and the world. It shapes our identity and provides insight into the experiences of those around us, fostering empathy and social connection (Pause et al. 2013). Therefore, studying episodic memory not only advances our scientific understanding of how memory works but also deepens our understanding of human experience.

This review aimed to examine how episodic memory develops, summarize key findings in the field, and highlight areas where further research may be needed. By bringing these perspectives together, the goal was to provide a clearer picture of episodic memory as a fundamental part of the broader memory system.

METHODOLOGY

The literature search was conducted using the database Science Direct. The keywords used were "episodic memory development". To refine the results, the filter for article type was set to "research articles", while no restrictions were applied to publication type, subject area, access type, or publication year. The search and article retrieval were finalized on July 9th, 2025. To ensure relevance and quality, only peer-reviewed research articles published between 2000 and 2025 in English were included. Studies whose main focus was not the development of episodic memory across human life, or that worked with non-human subjects, were excluded from the paper collection.

The initial search identified 53 research papers. After following the inclusion and exclusion criteria, the number narrowed to nine papers, which seemed to focus on the understanding of episodic memory and its development in humans. These studies were organized according to the age groups investigated: early childhood, middle childhood, and late childhood/adolescence.

RESULTS

The final number of papers that followed all the inclusion criteria and were included in this review was nine, which together cover a significant portion of childhood as well as some aspects of adulthood (Table 1). These papers were divided into age groups, as most of the papers compared multiple age groups or focused on one age group in particular, so the highlighted findings in these papers will best relate to age groups.

Table 1. Titles, authors, year, and age group are represented in the selected papers.

Title	Author and year	Age group
White matter structural connectivity and episodic memory in early childhood	Ngo et al. 2017	4 - 6 Early childhood
Hippocampal functional connectivity and	Riggin et al. 2016	4 - 6

episodic memory in early childhood		Early childhood
Remembering the past to envision the future in middle childhood: Developmental linkages between prospection and episodic memory	Coughlin et al. 2014	5-9, and adults Early/middle childhood
Examining the development of memory for temporal context and its underlying neural processes using event-related potentials	Bettencourt et al. 2021	7-12, adults Middle childhood
Developmental differences in the neural correlates of relational encoding and recall in children: An event-related fMRI study	Güler and Thomas 2013	8-13 Middle childhood
Changes in familiarity and recollection across the lifespan: An ERP perspective	Friedman et al. 2010	9-10, 13-14, 20-30, 65-85 Adolescence
The underlying processes of episodic memory development: From a unique contribution of representation to the increasing use of semantic organization supported by cognitive control	Frick et al. 2022	6-13 Middle childhood
Children's and adults' memory for the order of events in a museum: A preliminary study about temporal memory and its development using photo-taking and event-related potentials	Pathman et al. 2014	7-10 Middle childhood
Episodic memory during middle childhood: What is developing?	Guo et al. 2024	6-12 Middle childhood

Both papers that cover early childhood analyze facets of episodic memory and how changes in childhood affect the development of episodic memory.

First, Ngo et al. (2017) studied the brain's structural connectivity, focusing on the white matter, a part of the brain that is believed to be important for cognition and basic neural functions (Filley and Fields, 2016). The study aimed to analyze the differences in macro and microstructure of white matter in the brain and the effects of age on white matter. For the analysis of structural connectivity of white matter, diffusion-weighted imaging was used. This method allows researchers to better understand the structure of white matter in the brain (Schilling et al. 2023). Analyzing the macrostructure includes the physical volume of the tract and the extent of white matter, which connects the hippocampus to other brain structures. The analysis of the microstructure studies the fractional anisotropy (FA), which serves as a reference

to understand the integrity of white matter in the brain. A difference in the FA could serve to show a difference in the white matter of the brain. Ngo et al. 2017 aim to explain how such changes in the brain could affect episodic memory.

To study how differences in white matter caused by age affect episodic memory, the researchers used different methods to understand the children's episodic memory. The methods the researchers used were the children's memory scale (CMS) episodic memory tasks. These methods help with the analysis and comparison between the children's abilities to form memories, ideas, and conclusions. The findings indicate that there is no significant correlation between age and white matter structural connectivity. However, there is some correlation between white matter structural connectivity and episodic memory abilities. The correlation can specifically be seen with Hippocampus-parietal connections, meaning more mature or higher densely packed, myelinated axons between the hippocampus and parietal regions of the brain lead to better episodic memories, or at least better recollection of them.

The results also find a correlation between age and episodic memory as the 6-year-olds performed significantly better than the 4-year-olds in the memory tests, showing that the period between four and six years of age is significant for the development of episodic memory recollection, although white matter does not significantly develop during this time period.

Riggins et al. 2016 also focus on early childhood. Riggins et al. 2016 aim to understand the organizational differences in the brain and their correlation to age. The method used by the researchers to analyze the episodic memory abilities was a behavioral memory task and fMRI. The behavioral memory task was a test where the children were given toys in different rooms, and each toy was associated with a task to do, such as hugging it or drumming it. After a 1-hour delay, the scientists analyzed what the children remembered and what they did not remember. This helped the scientists understand the children's item memory abilities as well as context memory abilities. When analyzing the fMRI, the scientists focused on the hippocampus and examined its connection to other regions such as the temporal, parietal, prefrontal, and precuneus regions. In addition, both anterior and posterior regions were analyzed to see if there was any longitudinal specialization.

The results of these tests gave significant insight into episodic memory development in early childhood. The six-year-olds did much better when compared to the 4-year-olds on the behavioral memory test. This means the age correlated positively with memory scores. The fMRI shows that the hippocampal connectivity networks resemble adult memory networks, showing that the hippocampus is significant for memory, even in early childhood. Evidence of specialization also appeared, showing that different areas of the hippocampus are somewhat specialized in early childhood. A unique result appeared when analyzing hippocampal connectivity with memory regions. Six-year-olds with stronger hippocampal connections to memory regions had better episodic memory, so there was a positive relation; however, in four-year-olds, a stronger connection had a negative association with memory. An interesting discovery was connections outside of the hippocampus memory networks, positively related to memory in four-year-olds, but had a negative relation to six-year-olds.

These results show how significant the hippocampus is in early childhood and also suggest that the memory networks in early childhood are in a transitional phase, where younger children don't always use the networks that adults predominantly use, and their memory relies on other regions as well. At six years old, the hippocampus becomes more important for memory and becomes the main region for memory-related networks. This transition also results in significant improvements in episodic memory capabilities.

Overall, early childhood is a time when the brain reorganizes its memory-related networks, becoming more specialized and starting to rely more on the hippocampus, as well as an increase in specialization and overall episodic memory abilities. This change in organizations carries through to adulthood, where similar networks can be seen, with reliance on the hippocampus being a significant development that occurs during early childhood.

The next age group covered was middle childhood. Guo et al. (2024) studied children aged 6-12 to analyze how well they performed in episodic memory tests. The researchers studied the children's episodic memory through a treasure hunt where children hid different items themselves, and after a certain time delay, the children were asked what object they hid, where they hid each object, and when they hid each object. These questions were used so the researchers could understand the WWW integrated memory. They checked whether the children could recall all 3 aspects at the same time or whether they struggled. Guo et al. (2024) ran different questioning systems, which varied in the level of support, with one version giving more support with the questioning by giving options to the children, whereas the other version gave less support and was more open-ended, requiring free recall. This allowed the researchers to analyze the strategic retrieval ability and associative binding abilities of the children.

The researchers found that the 3 aspects of memory tested improved with age being item, spatial, and temporal memory. The integration of these memories also improved with age. When support was given in the questions, the younger children benefited more, suggesting that strategic retrieval abilities begin to develop during middle childhood. The research showed that the associative binding abilities developed linearly; however, some analyses hint that associative binding abilities may develop faster around the age of 9. A hypothesized reduction in memory performance due to neural networks reorganizing at the age of 11-12 did not occur.

Bettencourt et al. 2021 studied 3 different age groups to better understand how episodic memory develops over time. The age groups are 7-9, 10-12, and young adults. The participants were given items paired with contextual information, which they were to study. During retrieval, the participants were to determine whether or not they were given a certain item, and if they were, the participant would also be expected to remember the context to go along with the item. An ERP analysis was also given to find differences when recalling old vs new items, and correct vs incorrect recollection.

The results showed that a higher age resulted in a better performance on the memory-related tests, where adults performed better than 10-12 year olds, who performed better than the 7-9 year olds. The ERP showed that the 7-9 and 10-12 age groups both had differences in the ERP readings when comparing old and new items, and the difference was in a similar

fashion to the adults' readings. The difference between the children and the adults was mostly in the amplitude and the length, where the children had lower amplitudes and lasted longer. This difference in ERP readings correlates with less efficient and slower recall than adults; however, it shows that children in middle childhood have similar memory processes when compared with adults.

Overall, the results for the experiments show that temporal context memory improves significantly during middle childhood, and ERP findings illustrate that children have a similar thought process and generate the same neural signals; however, it is just less efficient and weaker than adults. Showing even more development occurs in later stages.

Pathman et al. (2024) focused on children aged 7-11 and compared them to adults. The participants visited a museum and they photographed around 120 exhibits in around 2 hours. As the participants took the pictures themselves, the events were personalized, as well as the order. After 1-2 days later the participants looked at pairs of photographs and they were supposed to decide which photo came earlier between the two. The researchers manipulated the distance between the events. Some were short as the 2 events were taken close to each other in time, while some were longer and had larger distances between each other. The researchers also manipulated the order of the given photos, as sometimes the photos were presented in the correct order, and sometimes the photos were given in the reverse order. During this process, ERP recordings were made. The ERP recordings were made to focus on whether short or long differences in temporal order changed the ERP results.

The results showed that both children and adults have a higher accuracy when the distance between the two events was longer, and the accuracy decreased as the distance between the two events in the pictures became shorter. Another observation was that adults showed a memory asymmetry effect as they performed better when the pictures were in the correct order of events, but this effect was mainly seen when there was a small time difference between events. The ERP showed a clear difference in neural responses when comparing short and long temporal distances, and this difference occurred in both children and adults. The ERP additionally showed higher sensitivity for the order of photos given.

Overall, these results showed that temporal order for episodic memory improves from middle childhood to adulthood, and children are not as sensitive to asymmetry; affect means that sensitivity develops in later stages of life. The ERPS suggest that both groups differentiate between close together events and faraway events, showing that this differentiation in neural processes has already developed before middle childhood.

Coughlin et al. (2014) focus mainly on middle childhood with five, seven, and nine-year-olds as well as young adults. In the paper, the participants created stories about past and future events. The changes in these stories were the temporal distance, which was 1 week compared to 1 year, and the temporal direction was also changed, comparing the past and future. After this, the patients subjectively rated the story's clarity, how easy it was to remember, and their perspective when remembering or telling the story. These stories were then given to the parents of close people with the patient in order to determine the accuracy of the story or the

event's plausibility.

The results showed significant improvement from the age of 5 - 9 when recalling events with contextual detail. Prospection or future stories were much less rich with contextual details than past events, and this was true in all age groups. The future events were considered harder to create stories for, and they were usually in a 3rd person perspective. Another finding in the paper was that the quality of the episodic memory of the past would correlate with the quality of episodic memories or the prospect of the future. This means that if a person has higher-quality memories of a past event, then that person is likely to have better-quality perspectives with more contextual details.

These results signify that episodic memory recall and prospection both improve; however, prospection does not improve consistently and is consistently worse than recalling past memories. The results also suggest that children rely on episodic memory to create prospects of the future, signifying another importance of episodic memory.

Güler and Thomas (2013) focused on the age 8 - 9 year olds and 12 - 13 year olds to analyze differences between the two age groups. The researchers analyzed episodic memory by analyzing fMRI scans of children associating different images. To explain a bit more, the Children were given pairs of unrelated objects and they were told to memorize them. There were two recall phases, one was silent and the other was verbal. In the silent recall phase, the children were given one item and told to press a button if they could recall the partner in their head. With verbal recall, the children were given the same objects and told to say the paired object aloud.

The results showed that the older children performed better than the younger children. The fMRI scans, when encoding the pairs of objects, younger children used the right dorsolateral PFC and right temporal cortex more than older children, whereas older children used the left ventrolateral PFC and parietal cortex more, and these areas are associated with encoding strategies. In recall, older children used the left ventrolateral PFC and the left interior parietal cortex, and during successful recall, these areas were used more strongly. However, younger children did not show specific areas of the brain that they used significantly, suggesting a more diffuse network.

These results signify a more specialized, concentrated neural network for recall and encoding as children move through middle childhood. The PFC is important for both encoding and recall, and a higher usage of the PFC shows more effective strategies in middle childhood and the beginning of adolescence. The results also show that the maturing of PFC-parietal networks is significant for memory improvements, along with the hippocampus maturing as well.

Frick et al. studied children around the age of 8-13 to focus on middle childhood. The method used to study episodic memory was by using a free recall task. The free recall task required the children to study 20 words from 5 different semantic groups, and they then recalled them without any cues. The Adjusted Ratio of Clustering(ARC) then measured if the children's recall was organized semantically. The researchers then gave representation tasks to the children to study the children's knowledge base and semantic knowledge. Control tasks were given to measure cognitive control, which were given to measure the children's ability to apply strategies

on their own. The results showed that some level of clustering does exist at the age of 8-9; however, clustering reliably improves recall at the age of 12-13. Younger children who used clustering usually did not have any benefit because of utilization deficiency, where they can not correctly utilize strategies, although they know of them. In 8-11-year-olds, the recall was supported mainly through representation, whereas in 12-13-year-olds, the recall was supported by both representation and clustering. The ARC only predicted recall in 12-13-year-olds.

The results from the paper highlight that a shift in recall occurs as 8-11-year-olds depend on knowledge representations, while older children's recall uses strategic organization to give better results.

Overall, in middle childhood, there are significant improvements in memory overall as a whole including information such as what, when, where, and the integration of these various aspects. Through brain scans, researchers have found that the neural networks in recall are more diffused in younger children and more concentrated and specialized in older children. Younger children in the middle childhood category begin to develop strategies for recall and organization. But it is not always effective. However, children on the older side of the middle childhood reliably use strategies for organization and recall, such as semantic clustering, which helps them perform significantly better in memory tasks, along with regions of the brain maturing on their own. Younger children will benefit more from support given when recalling than older children because of this difference in strategies for recall. Older children in the middle childhood category have similar neural networks to adults. However, they are still not as efficient, and that will develop at later stages.

The final paper, by Friedman et al., covers a diverse range of age groups, being 9-10, 13-14, 20-30, and 65-85. This paper will add information for the end of middle childhood and early adolescence, as well as adults, and even seniors. The paper gave the participants a list of words, and each word was studied for later recollection. In the test phase, the participants were given a mix of words that included words they had already given or old words, as well as words not previously given or new words. For each item in the list of words, the participants were to determine whether the word was old or new and whether they recognized the item with specific details and had contextual detail to go along with it, or whether they recognized the item but did not think of it with contextual detail. This study was repeated 4 times. ERP recordings were also made to recognize familiarity versus recollection. Young adults performed the best in the study, and they also benefited the most from the repetition of the trials. Recollection also increased with repetition vs familiarity, which did not improve. The children relied mostly on recollection and did not use familiarity as frequently, while adolescents used both styles of recall. Low-performing individuals evidently had deficits in recollection, showing a significant variability in that age group.

Overall, familiarity-based recall develops at young ages around middle or even early childhood, while Recollection develops later and peaks in young adulthood, declining slowly through age.

DISCUSSION

The importance of episodic memory is evident in many domains. For example, its role in eyewitness testimony has critical implications for the justice system, while research on memory retention informs educational practices. Episodic memory also intersects with mental health: traumatic memories can profoundly affect well-being, and understanding how such memories are encoded, recalled, and potentially modified may point toward strategies to reduce their impact (Pause et al. 2013).

Across the reviewed studies, episodic memory shows substantial improvement throughout childhood. In all age groups, older children consistently outperform younger ones on memory-related tasks, reflecting the steady development of this system across early life. During early childhood, contextual details, such as when and where an event occurred, improve markedly. The hippocampus becomes more functionally integrated within the memory network, shifting from a more diffuse to a more specialized role. White matter pathways linking the hippocampus to other regions also predict memory performance, underscoring its growing importance during this period.

In middle childhood, strategic processes that support memory recall begin to emerge. While initially inefficient, they become increasingly reliable in older children. Temporal aspects of memory also develop significantly, and episodic memory capabilities improve not only due to regional maturation but also because of large-scale brain reorganization, bringing the neural network closer to the adult pattern.

By adolescence, both familiarity and recollection are well-established and used reliably, though not yet at full adult efficiency. In young adulthood, episodic memory becomes highly efficient, with robust and differentiated patterns supporting familiarity and recollection. In older adults, recollection declines while familiarity remains relatively stable. Importantly, there is considerable variability among seniors: high- and low-performing individuals differ markedly in recollection ability.

Despite these insights, several research gaps remain. This review sought to understand developmental changes in episodic memory, yet many studies relied heavily on neural connectivity and activity measures (e.g., fMRI, ERP). Far fewer addressed how people *experience* episodic memories, such as their vividness or perspective (first-person vs. third-person). More research into these subjective aspects is needed.

Another limitation is the narrow age range of many studies. Most focused on one or two developmental stages, often leaving out transitions across the lifespan. Although challenging, studies that systematically include a broader range of age groups with comparable tasks would provide a more comprehensive picture of episodic memory development.

In addition, relatively few studies examined changes within adulthood. Young adults were often included only as a control or comparison group, and differences within adulthood were rarely analyzed in detail. This represents an important gap, given that episodic memory continues to change across the adult lifespan.

This review was also limited by its database coverage. Broader searches might have

identified additional relevant studies, especially those focused on subjective aspects of memory rather than primarily neural correlates. Expanding database coverage could strengthen future reviews and help shift the focus toward how episodic memory is *perceived* as well as how it is supported neurologically.

Future research would benefit from including wider age ranges and examining both neural and phenomenological aspects of episodic memory. Understanding not only how memory changes across the lifespan, but also how individuals subjectively experience their memories, would offer a more holistic account of episodic memory development and decline.

CONCLUSION

This paper aimed to examine how episodic memory develops over time, with a particular focus on perspective, while also addressing underlying neural changes. Episodic memory is central to human cognition and identity, shaping how individuals perceive themselves and others. A clearer understanding of both its mechanisms and phenomenology deepens not only our knowledge of memory itself but also our insight into broader aspects of human behavior and interaction.

Developmentally, episodic memory begins in early childhood with the ability to recall past events, albeit in a rudimentary form. During early and middle childhood, memory performance improves significantly as white matter connectivity strengthens and neural networks become more specialized. Strategic retrieval processes also emerge, though they are not always efficient at first. By adolescence, these strategies become increasingly reliable, and episodic memory capabilities continue to expand. In young adulthood, episodic memory reaches its peak, characterized by highly efficient and differentiated processes. With aging, some aspects of episodic memory remain stable, such as familiarity, while others, particularly recollection, begin to decline.

Overall, childhood represents a critical period for the growth of episodic memory, laying the foundation for later memory abilities. The capacities developed in these formative years not only shape lifelong memory performance but also influence identity, learning, social understanding, and mental health. Continued research into both the neural and experiential dimensions of episodic memory will further illuminate how it develops, how it changes, and how it shapes the human experience

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JASPER Play Therapy Benefits in Pretend Play By Ella Werber

150 CHARACTER SUMMARY

Independently wrote a literature review on the benefits of behavioral interventions for children with autism; published in peer reviewed journal.

ABSTRACT

Pretend play in children helps to strengthen their social, cognitive, and communicative skills. In pretend play, children can practice realistic scenarios using their imagination. For example, a child using a banana as a phone, or drinking from an empty cup. Pretend play not only builds on and strengthens children's imagination and social skills, but also requires these skills from the beginning to participate in pretend play. Additionally, pretend play requires children to understand the mental and representational states involved so that they are aware of what is being indicated in the game and can react accordingly. However, children with autism spectrum disorder (ASD) tend to exhibit weaker abilities to engage in pretend play. Children with ASD tend to display challenges with expressing and understanding emotions, and difficulty with imaginative thinking, which limits their engagement in pretend play. Because pretend play helps children build essential social communication skills researchers developed a play-based therapy called Joint Attention, Symbolic Play, Engagement, and Regulation (JASPER) to support children with autism in these areas. JASPER encourages a child to focus on both a toy and person at the same time. In effect, through play the child strengthens language, attention, social skills, and their capacities for symbolism essential to pretend play.

1 INTRODUCTION

The act of playing pretend is a common activity that children all around the world participate in. It is not only fun, but helps strengthen children's cognitive skills and symbolic capacities, counterfactual reasoning, and theory of mind. While pretend play is a beneficial way for typically developing children to gain social and cognitive skills, children with autism have a harder time participating in pretend play. Autism Spectrum Disorder (ASD) is a neurological and developmental disorder that hinders an individual's communication and social skills. Therefore, children with ASD have a harder time gaining and developing cognitive and social skills compared to typically developing children.

Typically developing children between 12-18 months old, are at the beginning of multiword comprehension, meaning they can respond to simple demands like, "Give me your hand," and are starting to use words purposefully, using a variety of communication tactics (Porter). Additionally, children at this age can play in parallel with other children in simple object centered games. At 18-24 months old, children can follow multiple simple demands and use words instead of gestures. At this age, play also becomes more symbolic and directed at themselves (ex. closing their eyes and pretending to sleep), then directed towards objects (ex. "Using a banana for a telephone"). At ages 24-36 months, children begin to correctly respond to

multiword sentences, understand negatives like “no” or “don’t” and begin to ask for things they want. They begin to play near other children and briefly engage in their play. At 36-48 months, children can participate and sustain a conversation for 3-4 rounds and ask many questions. Their concentration is significantly longer, allowing them to join in play with other children for longer periods of time, take turns with toys, and can plan out pretend play (Porter). At 48-60 months, children can listen for extended periods of time, can follow a couple of unrelated commands in the correct sequence, and have a more extensive vocabulary they can use in social play to solve problems, and can describe imaginary situations (Porter). They also begin to negotiate play and cooperate with children to achieve a common goal in play. At 60-72+ months, children are using complex forms of language and can have conversations with most people. Their attention span has significantly increased and they can split their attention between two things and they can negotiate rules, roles, and tasks during play with other playmates (Porter).

In this literature review, I compare the effects of pretend play and play therapy on the cognitive development of children with autism. As stated before, significant deficits in sensory motor and behavior skills, as well as social communication are seen in children with ASD. As a result, they struggle to participate in play and develop in the same way as typically developing children. To improve this, the Naturalistic Developmental Behavioral Intervention (NDBI) based intervention “JASPER” (Joint Attention Symbolic Play Engagement & Regulation) was created by Dr. Connie Kasari in the early 2000s to help children with ASD develop these skills and participate in pretend play.

1.1 Pretend Play

Pretend play is defined as an “as-if” state of play where non-real states are projected onto a present situation (Lillard et al.). Pretend play requires the transformation of objects and carrying out actions in a symbolic manner, as well as social dialogue, role taking and improvisation (Bergen). Children usually begin participating in pretend play individually between 18-24 months and as they continue to grow and develop, slowly start to incorporate other playmates (Porter). There are three forms of pretend play: object substitution, substitution of properties, and imaginary object play (Lillard). Object substitution is when one object replaces another, for example: a banana being used as a telephone. Substitution of properties is when a child acts like an object has an aspect that it doesn’t actually have, for example: pretending to eat out of an empty bowl. Lastly, imaginary object play is when a child pretends an object is there when it's actually not, for example: pretends to jump over a river in their living room (Lillard).

Pretend play significantly improves children's social, physical, emotional, and cognitive development. Its impact on development is so essential that it is considered a right of every child by the United Nations High Commission For Human Rights (Ginsburg et al.). Studies have shown that there is a significant link between pretend play and theory of mind, which is the understanding of others’ mental states. When a child has participated in pretend play to a frequent extent, they gain advanced understandings of their social partners' mental states, strengthening their social skills. Additionally, as the child becomes more aware that they are

adopting a view of the object that is different from its actual state, their imagination and perspective-taking skills become more advanced (Gosvāmī).

1.2 Autism Spectrum Disorder

Autism Spectrum Disorder (ASD) is associated with atypical patterns of brain development and neural connectivity. Consequently, individuals with ASD experience challenges in two main domains: social communication and restricted, repetitive patterns of behavior. (Lord et al.). Symptoms of ASD often include differences in language and communication development, variations in social responsiveness, and repetitive behaviors. As children grow, they may show less engagement in social interactions, narrower interests, and challenges with symbolic or pretend play as well (Hirota and King). It should be noted that since ASD exists on a spectrum, these symptoms and their severity can vary widely for each individual person.

One of the core areas affected by ASD is sensory motor skills, specifically shown through restricted and repetitive behavior (Lord et al.). In the DSM-5, RRBs (Restricted Repetitive Behaviors) are categorized into 4 subtypes: a) repetitive sensory motor movement, use of objects or speech, (b) insistence on sameness or ritualized patterns of routines, and verbal and non-verbal behaviors, (c) fixated interests that are abnormal in intensity and focus, and (d) abnormal interests in sensory aspects relating to the environment (Tian et al.). While turning the lights on and off may not seem like RBB, turning them on and off repetitively and intensely without any specific purpose is categorized as RBB. As a result of RBBs being frequently present in children with autism, their imaginative skills, and therefore play, are not being developed in the same way as typically developing children (Honey et al.).

The other core area affected by ASD is social communication skills. Social symptoms in children with ASD include impairments in conversational skills (e.g., taking turns in conversations or inability to take the listener role), expressive tone (e.g., rising and falling of voice pitch that helps with verbal communication), tendency to intensely focus and repeat on certain topics, and difficulty in expressing emotions (Williams White et al.). Additionally, a consistent social deficit in children with autism is a lack of non-verbal social gestures (e.g., pointing, showing, and giving). Their gestures are split into two categories: protoimperative and protodeclarative (Frye). Protoimperative gestures, which are absent in children with ASD, indicate what a child wants. An example of this gesture could be a child pointing at a toy on the shelf in the store. Protodeclarative gestures, also absent in children with ASD, are used to create shared experiences. An example of this gesture could be a child holding an object and extending their arm out for another person to see or placing the object in a person's hand to share the object (Frye).

While there is no cure for ASD, research has shown that therapies targeting language development, social responsiveness, and appropriate behaviors are the most effective treatment approach (Faras et al.). This paper will examine how autism spectrum disorder affects pretend play and explore how the JASPER intervention supports children with ASD in developing social and cognitive skills. First, the paper will discuss the role of pretend play in development, then it

will describe the challenges faced by children with ASD, and finally it will review JASPER as an intervention.

2 THE RELATIONSHIP BETWEEN PRETEND PLAY AND AUTISM SPECTRUM DISORDER

Pretend play is a way in which children can use their imagination to create a reality that they can control, separate from the real world. Through pretend play, children develop their symbolic thinking, counterfactual reasoning, and theory of mind. Symbolic thinking is the ability to understand/convey an abstract idea through the use of representative actions (Table 1) (Weisberg). When a child puts a towel over their back and starts waving around a spoon or putting on a crown, they understand that in the real world they are not wizards or royalty but they use their symbolic thinking to portray this idea; the spoon represents a wizard's wand and the crown indicates that the child is royalty. Through symbolic thinking, the child can develop their language skills. In pretend play, words are symbolic as they refer to objects used in a pretend state. Pretend play allows children to navigate relationships between words and objects, improving their vocabulary and language (Weisberg). Additionally, the child also develops their imagination, separating their mind from the concrete meaning of an object, for example, a spoon, to a more creative meaning, a wand (Petrović-Sočo). Secondly, through pretend play, children strengthen their counterfactual reasoning through exploring alternative realities and asking, “what if...?” questions (Table 1). By a child asking, “What if this spoon were a wand?” the child is creating an alternate reality for the spoon that is different from the real world in which it is a kitchen utensil (Weisberg). Counterfactual reasoning develops children's imagination as well as their judgement on alternate realities that can occur for objects during play and in general (Francis and Gibson; Wong et al.). Lastly, through pretend play, children strengthen their theory of mind (Table 1). Theory of mind is a child's ability to understand the role that the social partner takes on during play and what they are trying to represent (Weisberg). Through that understanding, the child can develop skills on how to react to those states. For example, if Child 1 started crawling around and barking, Child 2 would understand that Child 1 is trying to represent a dog. In the example, Child 2 understands that in the real world, Child 1 is a human being, but using their theory of mind, they ignore the true state of Child 1 and interact with their representational state, a dog (Weisberg). Theory of mind is strengthened as Child 2 is forced to conceptualize both possible states of the other person and react according to the play environment (Dore et al.).

Pretend play is important for developing cognitive, social, and linguistic skills. However, successful participation in pretend play also depends on having some of these foundational skills from the start. Because children with ASD often face early challenges in these areas, they may find it more difficult to engage in pretend play (Westby 20).

Table 1: Definitions and Examples of Cognitive Skills in Pretend Play

<u>Cognitive Skill</u>	<u>Definition</u>	<u>Example</u>

Symbolic Thinking	The ability to use symbols, objects, or words to represent something that isn't physically present	1. Using a spoon and waving it around to represent a magic wand 2. Putting on a crown to represent the idea that someone is royalty
Counterfactual Reasoning	The process of asking "what if...?" question and considering possible alternatives to certain events	1. "What if I started to say magic words and waving around a spoon and pointing it towards people?"
Theory of Mind	The ability to understand the representational states of other people and be able to react properly to those states	1. Understanding that in reality someone is waving around a spoon but in the play environment it is a magic wand so they should pretend that they are being spelled

In regard to pretend play, symptoms of ASD include stereotypical use of objects and challenges with imaginative thinking. Children with ASD struggle to understand two representations of the world - the real world we all live in, and another which is created through pretend (González-Sala et al.; Thiemann-Bourque et al.). Thus, an autistic child's symbolic thinking and counterfactual reasoning are not developed during play in the same way as they would for typically developing children. Additionally, children with ASD have difficulty understanding another person's mind (i.e., Theory of Mind) and therefore have difficulty understanding people in pretend play (González-Sala et al.).

Although children with autism have difficulty participating in free and spontaneous pretend play, they are able to participate in play when an action is modeled or instructed (Westby). For example, a child with ASD would find less difficulty pretending if someone were to ask them, "Can you show me how this spoon could be a magic wand?" Even though they would respond with a pretend action like waving around the spoon or pointing it at someone like they are casting a spell, they would be performing an expected action rather than spontaneously pretending (Westby). Since children with ASD rarely participate in spontaneous pretend play, they don't develop the social and linguistic skills that typically developing children advance through play; therefore, play intervention is a more productive way in which children with ASD can develop these skills.

3 JOINT ATTENTION SYMBOLIC PLAY ENGAGEMENT AND REGULATION

Joint Attention Symbolic Play Engagement and Regulation (JASPER) is a play therapy that improves a child's developmental behavior. Additionally, it improves the child's language, play and pretend abilities, and attentiveness by training them to focus on a toy and another person simultaneously (Elbeltagi et al.). During play, typically developing children are able to initiate Joint Engagement (JE), meaning the child and another social partner are actively engaging in play together. Typically developing children also initiate Joint Attention (JA), which

means that the child is aware of the social partner's presence. In the case of children with ASD, during play they might exclude the social partner by only focusing on the toy or event, impairing their collaboration skills and attentiveness (Adamson et al.; Shih et al.). Since children with ASD do not initiate JE or JA during play, intervention is necessary. Fortunately, JASPER specifically targets JE and JA in order to improve social interactions and communication skills in children with ASD.

Prior to starting the intervention, the play therapist/interventionist assesses the child's play and communication skills to identify developmental targets and to select certain age appropriate toys to help build upon the child's current play level. Specifically, JASPER interventionists create different play routines that encourage the child to interact with the adult and toy simultaneously to decrease their habit of only focusing on one or the other (Kaale et al.). During the sessions, there are different play routines packed with various opportunities for the child to interact with the toys and adult simultaneously (Figure 1). Throughout the routines, the interventionist and child constantly interact with each other through play, and the adult is creating an environment that encourages the child to engage in the different play scenarios. For example, if the child decided they wanted to build a tower with magnatiles, both the interventionist and child would interact with the tower together by both building it. As a result of the different levels and types of play, the child's communication, play, and engagement skills are being developed through different levels and types of play (Kasari, Gulsrud, et al.).

1. ❖ Interventionist assess child's play and communication skills ❖ Interventionist identifies appropriate toys and play targets	EXAMPLE: On the floor there are: ❖ Magnatiles somewhat built into a tower with pieces on the floor ❖ Small puzzle somewhat done but with pieces left
2. ❖ Environment is set up with toys ❖ Goal is that the child will interact with toys	EXAMPLE: ❖ Child begins to play with the Magnatiles ❖ Interventionist follows child by helping build the tower ❖ Interventionist moves puzzle out of the way so child can focus on tower
3. ❖ Interventionist and child create a play routine to nurture child's play and communication skills	EXAMPLE: ❖ Interventionist takes out toy people and places them in the tower ➤ Right after interventionist will say "person" ❖ The child will follow by putting another person in the tower ➤ Right after child will say "people in"

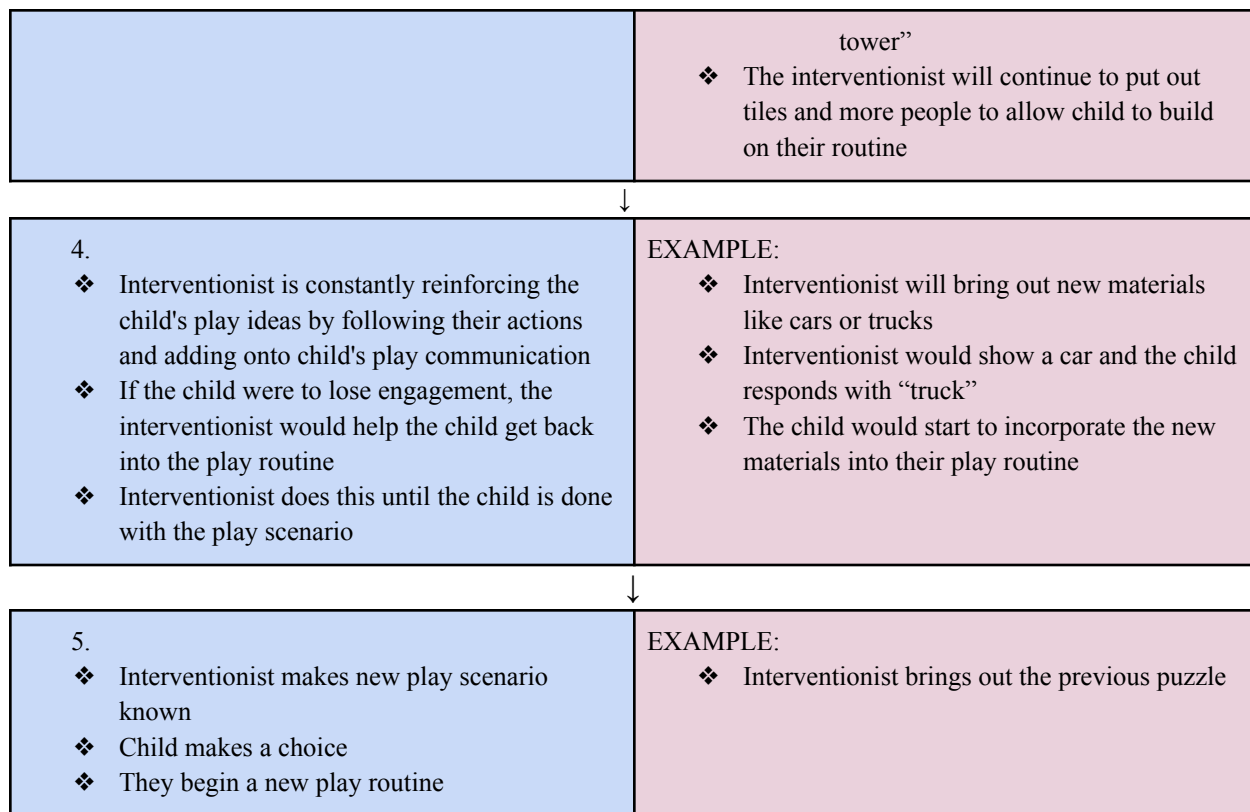


Figure 1: Routine Details of the JASPER Intervention. This figure outlines the details of the play routines used in JASPER (Joint Attention Symbolic Play Engagement Regulation) interventions. The intervention is completely child-led with the interventionist following the child’s actions and the materials used are all play related. The goal of the intervention is for the child to continually be advancing their play skills based on the play routines established between the child and interventionist.

JASPER studies have shown that after the JASPER intervention, children with ASD demonstrated greater play, joint attention, and social engagement compared to their entry in the beginning of the intervention (Shire et al.; Waddington et al.) Children in the intervention group showed a 40% increase in their participation and mastery in symbolic play (Table 2)(Chang et al.). Furthermore, children with ASD not only achieved successful symbolic play but also made progress in their imaginative, social, and engagement skills (Chang et al.). As a result of the JASPER intervention, children with ASD have the capacity to make meaningful cognitive developments just like TD children through pretend play.

Table 2: Comparison of Studies with JASPER Interventions

<u>Study/Review</u>	<u>Participant Information</u>	<u>Intervention Time</u>	<u>Outcomes</u>

Preschool Based JASPER Intervention in Minimally Verbal Children with Autism: Pilot RCT (Goods et al.)	3-5 year olds, minimally verbal with autism	30min x 2/wk - 10 weeks	- Strong results for improving diversity of play - Time unengaged in play decreased
Developmental Play Skills as Outcomes of Early Intervention (Chang et al.)	Pre-school age children	45-60min x 1/wk - 2-3 months	- Children in JASPER group demonstrated an increase of 8 different play types in their routine - Children in JASPER group demonstrated an average increase of 1 play level in their play complexity - 39.3% of children demonstrated a mastery of symbolic play when the intervention had ended
Joint attention and symbolic play in young children with autism: a randomized controlled intervention study (Kasari, Freeman, et al.)	58 children, 3-4 years in age	30min/day - 5-6 weeks	- Level of play in children participating in the play group increased 30% - symbolic play types increased 86%

Specifically, JASPER interventions improve autistic children's initiation of JA and JE, and as a result of these improvements, developments have been seen in communication skills and peer collaboration during play (Waddington et al.). When the child is able to more productively pay attention to the play therapist/adult and the toy simultaneously (JA + JE), the two parties are then able to develop the complexity and diversity of play. The goal of JASPER is to see the child use their imagination spontaneously to create new play ideas. As their engagement and communication skills continue to improve, the play therapist and child slowly work together toward more mastery of symbolic play (Kasari, Gulsrud, et al.). For example, a child who came into the intervention as the level of *pretend self* (a child extending actions on themselves (e.g., pretending to drink water from a cup) could leave the intervention at the level of *child as agent* (a child extending actions onto an object e.g., have a doll pretend to drink water from a cup)(Chang et al.).

Through strengthening the child's JE and JA, one possibility is that the JASPER intervention has also strengthened the child's theory of mind. In this case, as the child becomes more aware of the social partner(s) involved in the play environment, the child's skills in understanding who/what the social partner represents would become more advanced. Additionally, as play becomes more creative, it is possible that the child's symbolic thinking and counterfactual reasoning also strengthen. When the play environment becomes more complex, the child would ask, "What if..?" questions that would advance their representational thinking. Since these cognitive elements of pretend play have a lot of overlap, when one is strengthened

the others are likely strengthened as well. JASPER has improved children's participation in pretend play settings through strengthening their communication and engagement skills while also working on advancing their play complexity and creativity. In the same way that typically developing children develop their social, linguistic, and engagement skills through pretend play, JASPER offers autistic children development in the same skills, but through a more structured and targeted approach.

4 CONCLUSION

Multiple studies have shown that JASPER play therapy is a productive and beneficial way for children with ASD to strengthen their pretend play and social and communication skills. While JASPER was the only play therapy touched on in this paper, there are other therapies that exist to treat children with ASD, like 3i Play Therapy or Child-Led Play. Both these therapies are less intrusive and allow the child to lead the play routine while the adult or therapist follows along, but they yield similar positive developmental and social results as JASPER therapy (Elbeltagi et al.). Additionally, it is important to note that while JASPER generally targets attention, engagement, and play, participants will respond differently depending on their development and social and communication challenges.

Although JASPER has yielded many positive results in the cognitive development of children with autism, some might be opposed to the therapy. Some may believe that a con to JASPER and other similar play therapies is that they try to suppress autistic traits to fit into neurotypical standards by changing their behavior, mannerisms, and communication styles completely (Baiden et al., 2025). While this criticism is valid, the JASPER intervention is valuable and widely supported because it is more of a natural intervention than the alternatives. The intervention uses the child's interests to teach new skills, can take place in a natural setting like the home, and the interventionist engages with the child through imitating their behaviors.

While typically developing children develop their cognitive, social, and communication skills through pretend play, children with autism have more difficulty participating in pretend play and therefore, cannot develop the same skills. As a result, the JASPER play therapy was created to combat this issue. JASPER has not only yielded positive results in autistic children's successful pretend play, but has also significantly improved their social and communication skills as well. By targeting these areas, JASPER has helped children with autism develop the necessary skills to foster better peer interactions, language growth, and independence.

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Kazuo Ishiguro: Can't Teach an Old, Vain Dog New Tricks By Justin Song

Abstract

The endings of Kazuo Ishiguro's novels are deceptively happy, giving the illusion that the narrators progress forward when the reality is that they are much the same person as they were at the beginning of their respective works. While this insight is not necessarily a new one, there is little to no discussion on why these characters end up this way. This essay thus aims to ascribe this stasis in character to a common obsession by the narrators of Ishiguro's works to protect and preserve their pride. Through establishing this conclusion, other conclusions that utilize the endings as textual evidence can be clarified and the differences within this common theme can be accentuated to highlight, more deeply, Ishiguro's theories on psychology.

Introduction

By the endings of many of Ishiguro's novels, their narrators, after spending the whole novel looking back on their life and reflecting on all the experiences they have had, will then turn towards the future with a brighter outlook on life. Especially in his earlier works, *An Artist of the Floating World* and *The Remains of the Day*, these endings are decorated with bright imagery and joyful, casual conversations, allowing Ishiguro to imprint a relaxed tone that gives these books the appearance of being nicely wrapped up. The narrators, at first glance, emerge from their introspections as changed men for the better. However, beneath this guise of progress, Ishiguro actually conceals a reality that is much more cyclical; his narrators do not come out of their stories the changed people their newfound sentiments and the novels' happy tones would have the reader believe, but instead emerge as much the same person they were at the beginning of their books. Their stories, essentially, are more akin to loops rather than arcs.

This is not necessarily a new insight; some scholars, such as Dr. Yuqing Jin, have already commented on the "true" nature of Ishiguro's endings. For example, Dr. Jin observes how, in *the Remains of the Day*, "all effective reflections were short-lived, and Stevens quickly moved away from confronting his normal inner needs after a brief period of grief or questioning" (Jin 194). However, while some may have identified the reality of the endings, there is little discourse as to exactly why Stevens and the other narrators do not grow after their introspections. Ishiguro himself said in a 2000 interview that he is "more interested in what people tell themselves happened rather than what actually happened," but does not mention anything about why these people tell themselves a distorted reality (Dunn). With so much criticism on Ishiguro utilizing his endings to prove their own conclusions, knowing how and why the endings have come to that point is imperative to ensure that the interpretations of endings in these papers align with the broader context of the novel. This essay aims to diagnose the primary cause of this cyclicity in Ishiguro's work as a common obsession to protect one's pride through a close reading of the narrators and endings of his most famous works, *The Remains of the Day* (RD), *An Artist of the Floating World* (AFW), and *Never Let Me Go* (NLMG).

The Remains of the Day

Of all of Ishiguro's novels being studied in this paper, *Remains of the Day* is most clear in its relationship between pride and its narrator's stagnancy. Stevens is a butler who, in the prime of his career, served Lord Darlington, an influential man who has since been disgraced in postwar England due to being a Nazi sympathizer. By the time of the novel, Stevens now works for a new master, Mr. Farraday, who encourages Stevens to go on a motoring trip along the English countryside for vacation. During this trip, he reminisces on his career and slowly becomes aware of the fact that Darlington was not the man he thought him to be and that Stevens failed to have the significant impact on the world he dreamed of having. By the end of the novel, he appears fully disillusioned, believing his career to be a waste, until a passerby teaches him to enjoy the "remains of his day," or the rest of his life, without worrying so much about what has happened in the past. The novel closes with him returning to Darlington Hall, taking with him a renewed interest in bantering, which he believes "lies the key to human worth", saying:

"Perhaps, then, when I return to Darlington Hall tomorrow... I will begin practising [bantering] with renewed effort. I should hope, then, that by the time of my employer's return, I shall be in a position to pleasantly surprise him." (RD 245)

Acknowledging Stevens' emotional coldness and inability to interact naturally with other people outside of a professional context, it makes sense that this resolution should be perceived as a positive one. His focus on "bantering," a practice he struggles with and stresses about from the beginning of the book, leads the reader to believe that he is going to finally ease himself around people and rid himself of the stiff and unnatural conversations that are in abundance throughout the novel. However, despite initial appearances, Ishiguro embeds signs that signify there was no change of considerable consequence in Stevens' character despite his newfound resolve. For one, there is an irony within Stevens' proclamation in the quote above that he "will begin practising with renewed effort" with regards to bantering. Most apparent is the fact that bantering, or simply conversation, is not something that one rehearses but rather a skill that is naturally built up over time. Ironically, practicing conversation to the extent that Stevens is suggesting he is going to could actually turn his conversation to become even more contrived, which is even more apparent given the methods he's used prior, which focus on exercises to "formulate witticisms" based on a comedy show he watches (RD 131). Stevens' inability to grasp that bantering does not equate to the manufacturing of witticisms and a rehearsed approach to an activity that is natural and frequently relies on improvisation will likely mean that his problems relating to interpersonal connections will persist despite his renewed efforts, demonstrating his paralysis.

Stevens' relationship with the concept of "dignity" throughout the work can explain the inability to change above and is in itself another way to affirm the lack of growth in his character. Throughout the book, he attempts to find his definition of the term "dignity" because he believes it to be the key to determining what makes a great butler. The main definition of dignity that he

decides on for the majority of the work is described in the following passage, to which he compares his own career and service to:

“[Great butlers] wear their professionalism as a decent gentleman will wear his suit: he will not let ruffians or circumstance tear it off him in the public gaze; he will discard it when, and only when, he wills to do so, and this will invariably be when he is entirely alone.” (RD 43)

Essentially, Stevens believes the aim of a butler is to maintain a sense of composure and to present oneself as a fully devoted and perfect butler at all times no matter what obstacles may tempt one's deterrence. However, in practice, as evidenced through the many episodes Stevens relates to the reader, this often means completely neglecting one's personal needs and emotions, going so far as to continue his work in spite of his father's death, whose care he defers to Miss Kenton. Luckily, by the end of the book, this definition begins to change and is seemingly disproven by the old man on the bench. Steven realizes by the end that “[Lord Darlington] chose a certain path in life, it proved to be a misguided one, but there, he chose it... As for myself, I cannot even claim that... I can't even say I made my own mistakes. Really—one has to ask oneself—what dignity is there in that” (RD 243)? Here, Stevens appears to be gaining independence in thought and an understanding that his mad pursuit of making an impact on the world led him to be oblivious to exactly what impact he was making or if he was making one at all. However, as Dr. Jin has argued, he very quickly returns to beliefs that, though seem new, resemble quite strongly ones that he has previously related. For instance, after just lamenting over the fact that he did not choose his own path, he immediately reverts back to the belief that “our fate, ultimately, [is] in the hands of those great gentlemen at the hub of this world who employ our services,” and this undoing of his sudden outburst is further represented in the symbolic importance of the butler (RD 244). By returning to Darlington Hall, Stevens retethers himself to these “great gentlemen” after having the freedom represented by the road trip embarked in the book. He relinquishes his independence and goes back to his job of taking orders from his master, essentially barring him from ever choosing his own path, which he regretted so deeply just a page prior. Furthermore, his approach to mastering how to banter is so rehearsed and explicitly for the purpose of pleasing Mr. Farraday that it is evident that Stevens is only going to further adorn the “coat” that he donned to match his old definition of dignity with formulated witticisms rather than taking the garment off more frequently, ultimately illustrating how Stevens has not changed at all by the end of the work.

In addition, the fact that he is returning to his job so soon symbolizes a cyclicity that goes against what the man on the bench tried to teach Stevens at the end of the book, that one should enjoy “the remains of their day”, or the rest of their lives; “We've all got to put our feet up at some point. Look at me. Been happy as a lark since the day I retired... you've got to keep looking forward” (RD 243). There is something to be said in the fact that Stevens, rather than metaphorically “putting his feet up” and enjoying the remains of his life, instead immediately

prepares to go back to Darlington Hall despite the fact that Mr. Farraday is still a week away from returning. Whether he would be practicing bantering or sweeping shelves, these actions are the same as those he performed at the beginning of the book; they are the strict duties and responsibilities of a butler. This example makes apparent that his actions, like his character, remain unchanged despite him appearing to be a changed man by the novel's end. Now, having seen exactly how Ishiguro exhibits Stevens' stasis in character in the ending, we can now connect this with the pride Stevens shows throughout the rest of the novel.

An interesting pattern throughout Ishiguro's books is that his narrators, at first, present themselves as extremely humble, but throughout the book they begin to subconsciously reveal their true pride of the work they have done over the course of their careers. Stevens is a prime example. This is most explicitly demonstrated in his change of attitude towards the conference; before describing the event in detail, he prefaces that while he considers it a "turning point in [his] life", he also asserts that it does not make him, necessarily, a "great" butler and that he is only telling us the event to give an example of a small amount of the "dignity" he has tried to explain to us so insistently (RD 70). However, by the end of the story, his language changes from a humble tone to one that is much more assertive and forward. He instead questions, regarding his pride, "why should I hide it?", revealing his true feelings that, when recalling the event, he feels a "great sense of triumph" (RD 110). Of course, there is nothing wrong with being proud of the work one has done. The fact that Stevens initially attempted to hide his pride from the reader could possibly be attributed to his guarded nature and unwillingness to seem arrogant, which was also displayed in an interaction with Mr. Farraday at the beginning of the book. However, while pride in itself is not an issue, the proof of its existence in Stevens' character, despite his initial denial of it, allows us to examine his obsession with the trait, and thus link it as the cause of Stevens' cyclicity.

Stevens' main flaw in his relationship with pride is his obsession to protect it, which he most clearly accomplishes through twisting or denying facts that would ultimately destroy his own self-worth. This is done through both the hiding of his own ideals and the subsequent vindication of Darlington's character. The issue at stake here is the fact that Stevens prides himself on his alignment with his own classification of "dignity", which he believes is the ultimate goal for a butler to achieve. However, while dignity is partly on the "professionalism" of the butler as described earlier, he has also ascribed it to be on the morality/influence of their master; the more a master is doing to effect positive change on the world, the more dignity his butlers have. In this regard, Stevens has always considered Darlington to be a positive in this category. However, when he realizes that Darlington is not the man he once thought him to be and that Lord Darlington would actually be a detriment to Stevens' "dignity", Stevens tries to protect his pride by trying to hide this measure. While he opens very early on in the novel about the service side of dignity, he does not mention the master side until the middle, which he describes as a "rather unsettling experience" having not "properly considered" this aspect of dignity since the matter was so "close to [his] heart" (RD 113). Once he admits this criterion for

“dignity”, he then tries to rebuke attacks against Lord Darlington for being anti-semitic, as shown below:

“In particular, let me clear up this matter of a supposed bar against Jewish persons on the staff at Darlington Hall... I am able to refute it with absolute authority... One really cannot guess the reasons for these absurd allegations—unless, quite ludicrously, they originate from that brief, entirely insignificant few weeks in the early thirties when Mrs. Carolyn Barnet came to wield an unusual influence over his lordship.” (RD 145)

From this quote we can see both the vehement denial and yet the self doubt within Stevens. In his intensity he betrays through the excess of denial that there is something else to the story, which there is; later, he reveals that two maids were dismissed solely because of their being Jewish. Stevens’ attribution of his own “dignity”, or self-worth, to having served a “worthy” master explains much of the fervor in his defense of Darlington. After all, should Stevens admit that Darlington was an anti-Semite, his master would no longer be “worthy” and he would thus lose much of the “dignity” that he had, as defined by his own terms. Ultimately, Stevens’ obsession with his own pride and protecting it in spite of all that has come to light about Darlington has caused him to hide his own beliefs and lie about the past in order to maintain his own self-image of a butler with “dignity”.

It is crucial to note that Stevens created the parameters for what constitutes dignity himself, causing the word to take its own meaning to him. This logically entails that, should new revelations or ideas occur, the meaning of “dignity” can change, and thus what Stevens prides himself on could evolve. However, it does not. Rather than realizing, in light of Lord Darlington’s fall in status, that perhaps the status of oneself should not rest on the actions of others and thus his definition of dignity should adapt to suit that, he instead tries to hide the parameter and Darlington’s true character from the reader, and to himself, in order to maintain his pride/self-worth. His attachment to his own beliefs on the quality of dignity, and perhaps the lack of humility needed to admit that he was wrong at first and make change, are absent in Stevens. His obsession with protecting the pride that was founded on his ideals has caused him to fail to realize that the ideals themselves are not the ones he should follow, even after his introspection. Consequently, since Stevens never changes his ideas of dignity, no meaningful change can occur within him after the story. As we see in the ending, Stevens quickly re-dons the “coat” of dignity and professionalism that he prided himself on wearing throughout the book, with his immediate return to Darlington Hall a symbol of him trapping his growth under his own self-esteem and addiction to its preservation.

An Artist of the Floating World

The narrator of Ishiguro’s *An Artist of the Floating World*, Ono, is the most overt about his pride of the narrators discussed in this paper. Ironically, he begins the novel by discussing his indifference to his own status, claiming on the very first page that he was a man of “modest

means” and that he has “never at any point in [his] life been very aware of [his] own social standing” (AFW 3, 24). Like Stevens, Ono begins the book by putting up a facade of humility that is broken down throughout the course of the novel, but *An Artist of the Floating World* differs in exactly how the reader comes to the realization of Ono’s narcissistic tendencies. While Stevens reveals his “great sense of triumph” explicitly, telling the reader his true thoughts, Ono never does and it instead must be extrapolated from the repetition of the fact that he does not know nor care about his social status. The constant need to keep mentioning this indifference, ironically, suggests that the opposite is true. While he does not say so himself, he also includes many anecdotes throughout the novel of other people praising his accomplishments, such as when Kuroda does so while drinking at the Migi-Hidari:

““Indeed, as the instance [Ono] has just related amply illustrates, his reputation has now spread beyond the world of art, to all walks of life... His reputation will become all the greater, and in years to come, our proudest honour will be to tell others that we were once the pupils of Masuji Ono.”” (AFW 25)

The combination of repetition and anecdotes clearly demonstrate the reality that Ono is deeply obsessed with his own status. The fact that the anecdote above is relayed at all is again proof of his true pride. He explains to the reader soon after that “there was nothing remarkable in all of this” and that speeches of his pupils’ loyalty were common (AFW 25). It is because of this apparent unremarkableness that makes the fact he remembered this speech specifically more telling of his inclination towards his own status. Indeed, though he still props up the image that he does not care for his social status, he does admit that he felt a “warm glow of satisfaction” during the whole incident, again demonstrating his true feelings.

More importantly, however, is the fact that Ono is trying to protect his own pride. Of course, as established with Stevens, pride itself is not an issue, but the obsession to preserve it is. While both narrators suffer greatly from this, the two differ in the method to which this pride is protected. While Stevens pushes away certain facts in order to maintain his own image, keeping his pride to be based largely on his definition of “dignity”, Ono instead has his pride hop between various criteria in order to keep the pride from crumbling under the current expectations of society. This is most evident in the April 1949 section of the work when one compares Ono’s attitude towards Shintaro, who comes to request for Ono to absolve him from his association with the China campaign at the beginning of the section, and the sentiments during his reflection of Noriko’s *miai* at the end. At the beginning, Shintaro, looking for a position as an art teacher, needs Ono to write the school a note that Shintaro’s views do not and did not align with those of the China propaganda campaign during World War II, to which Ono questions:

““Shintaro... why don’t you simply face up to the past? You gained much credit at the time for your poster campaign. Much credit and much praise. The world may now have a

different opinion of your work, but there's no need to lie about yourself.'” (AFW 103-104)

Here, the pride Ono displays is for the work they've done on the China campaign and, as a whole, the propaganda movement. Despite the world having a different opinion, as he states, he insists that Shintaro does not lie to himself about his role in it because of the credit he received at the time for his participation. This repetition of “much credit” in consecutive sentences highlights this conclusion, and this focus on the credit Shintaro received and, presumably, Ono as well means that Ono himself is attached to the acclaim he had received for his work at the time and is proud of it. The subsequent paragraph where Ono strips Shintaro of his dignity by having him leave unacknowledged may at first suggest a similarity to Stevens. Ono's unmoving figure represents a firm pride in what he's done in the past, turning away from the ideas of the future, towards the moving Shintaro. His staticness and refusal to look towards the past is reminiscent of Stevens' own method of turning away from the present reality of the world. However, Ono's pride is not a fort like Stevens', unmoving yet protected, but rather a refuge, which seeks new shelter when the previous one crumbles. At the end of the section, upon reflection of Noriko's *miai*, in which he had blurted that he believed that a lot of this work was a mistake, he shifts the source of his pride from the work itself to the fact that he has “taken responsibility” for the mistakes he has made over his career, saying: he “find[s] it hard to understand how any man who values his self-respect would wish for long to avoid responsibility for his past deeds... It is surely a thing far more shameful to be unable or unwilling to acknowledge them” (AFW 125). This quote, of course, directly contradicts what he had said to Shintaro at the time. Rather than facing the world's “different opinion” of the work they have done, Ono instead goes along with it and, upon admitting the mistakes he made during his career, then takes pride in the fact that he had made such a concession.

However, it is important to note that this shift in pride happens upon Ono's reflection of the events in the *miai* rather than during the *miai* itself, as this is what distinguishes the above change in sentiment as a protection of his pride rather than an organic maturation of his character. If it were not, then Ono would have, as some people such as Mr. Maloney of the *Japan Times* believe to be, “real guilt over his past” (Maloney). I disagree. These people may point to the fact that the episode with Shintaro happens a few days after the *miai*, despite being related to the reader before the *miai*, as evidence against this assertion that Ono is, like Stevens, desperately trying to protect his pride. After all, if the event that is meant to show change happens before the event that is meant to show stagnancy, has Ono's pride really shifted? This is why it is the reflection of the event, rather than the time of the event itself, that matters. He admits that his declaration of the mistakes of his career would not have been made so easily had “circumstances not impressed upon me the prudence of doing so” which, given the context of the *miai*, meant the uncomfortable stares of Mitsuo Saito, a student who attends the college Ono's former pupil, Kuroda, teaches at (AFW 124). The statement is almost forced out of him rather than being the result of a realization he has personally had about his career, and it is one that

goes against the current source of pride he had established: from the work itself. However, because uttering this statement completely destroys his own self-image, Ono's pride must take solace in a new criterion, and so he thus emphasizes this "owning up" to his mistakes as the new source. Thus, as claimed earlier, Ono is similar to Stevens in the fact that he is trying to protect his pride, but his exact method to do so is different. However, despite the difference in method, Ono still comes out of the novel unchanged as a result of this tendency.

Like the ending of *Remains of the Day*, *An Artist of the Floating World*'s ending has a very hopeful tone, with very sunny skies and Ono wishing the younger generation the best of luck in the rebuilding of Japan. Again similar to *Remains*, there is an apparent emphasis on the future and looking forward, which would logically suggest Ono himself has undergone a change. However, upon closer reading, Ishiguro subtly asserts that this is not the case. For starters, while the world around him is bustling and eagerly working, he himself is stationary, sitting on a bench. By inserting this contrast into the ending, Ishiguro underscores the reality that Ono has not changed significantly throughout the course of the novel in spite of the fact that the society around him has. While Ono acknowledges this change in society and wishes the world luck, he himself is not changing with them. This is further emphasized by the fact that Ono is sitting on the former property of the Migi-Hidari, the nationalistic bar he helped to establish before WWII. More specifically, he believed that "the bench occupies a spot very close to where our old table in the Migi-Hidari would have been situated" (AFW 205). Through making this connection, we see how Ono is almost bound to his past, which is further accentuated by the Migi-Hidari being the embodiment of the "regressive" spirit he had subscribed to so ardently back then, which the world now considers "wrong". Even further, this table is also the table where his pupils would "take to making speeches of a loyal nature to [him]," implying not only an inability to grow but an inability to step out of a bubble that showered him with so much acclaim and praise (AFW 25). Ono's source of pride being specifically the fact that he has admitted his mistakes means he feels no obligation to do something about said mistakes, leading to his shift in pride amounting to nothing more than shallow acknowledgement, as evidenced by the end of the novel. Thus, because of this, as well as the similarities to Stevens, Ono's inability to grow as a character is, too, ultimately a result of his desire to protect his pride.

Never Let Me Go

Never Let Me Go's Kathy is, at first glance, very different from the other two narrators discussed so far. While Ono and Stevens are older men both past their prime and led careers full of grand ambitions that went unrealized, Kathy is a young woman who is still working and is seemingly modest in comparison. Rather than the former two's ambitions to have an effect on the world, Kathy's ambition lies largely within the realm of her profession as a carer of donators, or human clones whose organs are harvested for scientific purposes. Because of these smaller ambitions, *Never Let Me Go* takes the focus off Kathy's professional life and more on her personal life with Ruth and Tommy, only coming around to it in detail by the final part of the book. In an interview, Ishiguro claimed that while self-deception was a theme he wanted to

explore in his earlier books, “*Never Let Me Go* isn’t concerned with that kind of self-deception. So I needed my narrator to be different. An unreliable narrator here would just have got in the way” (“Kazuo Ishiguro Author Interview”). Of course, Ishiguro is right to say this. Many scholars from all fields, such as Dr. Anne Whitehead in “Writing with Care: Kazuo Ishiguro's ‘Never Let Me Go’”, have discussed themes such as biomedical ethics or divides in society and Ishiguro is experimenting with a genre of soft science fiction that deviates from the strictly realistic fiction of his previous works (Whitehead 2). Given the amount of change that *Never Let Me Go* brings to his oeuvre, it makes sense that “self-deception” is not his focus. However, just because his primary concern with the novel is not the self-deception so prevalent in his other works does not mean that it is not there. Even if it is on a subtler scale, Kathy still exhibits the same sense of pride Ono and Stevens have and the same desire to protect it, which then becomes a large factor in her own cyclicity by the end of the book.

Kathy’s pride largely stems from her belief that she is doing a good job in her work as a carer, boasting that her donors “have always tended to do much better than expected. Their recovery times have been impressive, and hardly any of them have been classified as ‘agitated’, even before fourth donation” (NLMG 8). It is, as we have established, not a bad thing in itself to take pride in one’s own work. And, unlike Stevens and Ono, Kathy is much more straightforward with stating her pride by being clear at the start of the book rather than the reader having to piece it together throughout the other two novels. However, this one statement does not tell the whole story. It only seems benign at the start because Ishiguro withholds the context of Kathy’s world, and while the reader may question what a “donation” is or what an “agitated” classification entails, the positive tone of Kathy, claiming that she’s boasting about her work, largely overshadows these concerns. Thus, while in the other two novels readers learn of the narrators’ pride throughout the course of the novel and soon realize the detrimental nature of said pride, in *Never Let Me Go* the pride is revealed early on and its harmfulness is hinted at over time as Ishiguro reveals more information about the world that surrounds Kathy and the unknown terms above show their true meanings.

The way Kathy protects her own pride is astonishingly similar to that of Stevens in that she too subconsciously pushes away facts and information that would threaten her self-esteem. Once Ishiguro reveals the true meaning of “donations” and that the country is forcing clones to assist in harvesting other clones’ organs as “carers”, Kathy’s earlier statement that she takes pride in this work turns from relatively harmless to one much more concerning. Dr. Bruce Robbins’s analysis of one of Kathy’s statements, that “the recovery rooms are small, but they’re well-designed and comfortable,” sheds light on her attitude towards the institution as a whole (NLMG 21). He explains:

“Kathy’s brisk efficiency leaves no space for surprise at the fact that there are recovery rooms; that recovery rooms exist in the first place only because of “donations”; that the existence of donations and recovery rooms signals a suffering that is beyond any possible compensation. The sentence structure seems engineered to guarantee that the best will

always be made of a bad situation, with no acknowledgment that the situation will always be bad because the same system has also begotten it.” (Robbins 8)

Robbins’ interpretation of Kathy’s behavior in regards to her employer asserts that she is trying to ameliorate the minor problems with the system and “make peace” with her fate, as well as trying to get her donors to do the same thing. With regards to pride, this brushing off of the greater problems and atrocities of the system, instead merely accepting them as “right” without much question, is Kathy’s own way of maintaining her pride. Had she thought about the reality of her employer and realized how inhumane the system is, the fact that she is good at her job as a carer would mean nothing anymore and she would thus lose her main source of self-esteem. Of the other narrators, Kathy’s story draws many similarities between her and Stevens. Both have immoral employers in the donation institution and Lord Darlington and both are subtly aware of this fact but turn a blind eye in order to protect their own pride from reality as a result of them attaching their pride to the quality of the job they are doing. In drawing these parallels, one would thus conclude that Kathy, too, comes out of the novel largely unchanged, to which *Never Let Me Go* makes relatively explicit.

The ending of *Never Let Me Go* emphasizes the unchanging nature of Kathy in a way that shows how that stagnancy is a direct result of the protection of her own pride explained above. The book ends on Kathy visiting Norfolk, which in the book represents lost memories, and imagining Tommy walking towards her after dying from the donation process, with Kathy saying:

“The fantasy never got beyond that - I didn’t let it - and though the tears rolled down my face, I wasn’t sobbing or out of control. I just waited a bit, then turned back to the car, to drive off to wherever it was I was supposed to be.” (NLMG 256)

Driving off to “wherever it was [Kathy] was supposed to be”, presumably a place related to her work as a carer, mirrors closely the end of *Remains of the Day*, with Stevens intending to drive back to Darlington Hall to resume his duties as a butler. In both, we see symbolically a return to their old selves, which in Kathy’s case means continuing to subscribe to the ideals and praise from the institution that fuel her pride in spite of its immorality. She purposely suppresses her pain and longing for Tommy, whose death is the fault of the donation system itself, in order to swiftly return to her job and said system which has just caused her so much pain. Her motivation for continuing her job and suppressing her emotions, then, can only reasonably be explained through pride and her method of protecting it. It is the desire to maintain the pride she gets from doing her work well that compels her to quickly get back to work rather than stay at Norfolk. It is also her desire to protect this ego that prevents her from letting her think about Tommy for too long, as in doing so there is a risk that she would connect his death with the institution who gives her so much praise and thus destroys this pride. While some may point to the fact that Kathy does confront the cruelty of the institution through seeking a deferral and

comes to the epiphany that, regarding their lives, Tommy always “knew”, she quickly brushes this realization aside (NLMG 244). In fact, she explicitly states on the first line of the following chapter that “nothing seemed to change” after realizing deferrals were a myth and, when things ultimately did change, it was Tommy who initiated it through trying to find a different carer or in his mannerisms rather than Kathy (NLMG 246). Here, we actually see yet another parallel between her and Stevens, who both by the end of the book have a bit of a revelation that does not materialize because of how quickly they move back into the establishment they attach themselves to, a similarity that is explained by their common method of preserving their pride. Thus, despite Ishiguro claiming that *Never Let Me Go* is not concerned with self-deception, Kathy becomes his third case study into the relationship between pride and growth within a person. By mirroring much of Stevens in her story, she helps to create a more concrete conclusion in Ishiguro’s oeuvre of how pride’s protection stunts one’s growth.

Conclusion

Throughout the three case studies of Ishiguro’s major works, we have been able to identify his belief that the desire to protect one’s pride is a key factor in inhibiting one’s growth. While in some of his works, *Remains of the Day* and *An Artist of the Floating World*, Ishiguro attempts to disguise stagnancy as progress, beneath the surface we see that his narrators never attack the core of the issue, avoiding it while instead focusing on changing the unimportant. Through understanding the significance of the similarities between the narrators’ prides and their methods of protecting them, the differences can be accentuated to reveal more about how Ishiguro handles the emotion of pride. Why exactly does Ono shift his source of pride as opposed to Kathy and Stevens’ adherence to just one? What variation does it cause between the fate of the three narrators? These differences now become all the more interesting and telling as to Ishiguro’s insights on the human ego. Another question that could be pursued further is the accuracy of Ishiguro’s argument on pride’s role in growth given the current psychological research of today. Of course, while Ishiguro’s argument makes sense, humans are not nearly as structured or logical as literature can sometimes treat them as, and thus scientific research is needed to apply these conclusions to other disciplines. In the meantime, however, Ishiguro encourages us to look into ourselves and search for our own problems in this introspection. Hopefully, unlike his narrators, us readers of his work can face reality more honestly.

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Designing the Ideal AI Healthcare System: Learning from Past Successes and Failures

By Nikhil Kumar

Abstract

In recent years, Artificial Intelligence (AI) has gained a vast amount of attention in the field of healthcare as AI-based systems developed in the last few years have shown the potential to yield massive benefits to both patients and medical professionals. However, their implication in the real world has been met with mixed reviews as there has been a significantly higher number of failures compared to successful deployments. This paper takes a look at both examples of successes and failures within the complex landscape that is the implication of AI in healthcare to identify the key factors that influence whether an AI system will make a positive impact in the field of healthcare.

An AI system is a fully developed tool that applies an AI model in real-world clinical settings to aid with decision-making and patient care. For example, DeepMind made use of diverse training data along with collaboration from leading institutions to develop a system that was able to be implemented in clinical settings with success. In sharp contrast, this paper will also take a look at IBM Watson for Oncology, which stands as one of the most notorious examples in recent times of how disastrous AI systems can be in the field of healthcare if designed with fault. Furthermore, this paper also proposes a model for what an Ideal AI system in healthcare looks like with a specific focus on the detection of conditions such as diabetes and heart failure before symptoms appear on the surface. Looking back at these past examples of successes and failures, this study aims to outline how further AI systems can learn from these mistakes and achieve lasting benefits in a clinical setting.

1. Introduction

The capabilities of technology are constantly evolving. Most recently, the world has seen the emergence of Artificial Intelligence and the potential power it holds in the facets of daily life (Elliot, Anthony). For example, many people begin their day by unlocking their phone. Apple's face ID uses AI to convert one's face into a unique set of numbers that act as one's unique identifier (Devlin, Hannah, et al.). A key area where AI could have massive implications would be in the field of healthcare. AI yields tremendous potential to improve the lives of both patients and medical professionals (Khanam, Mousumi, et al.). For instance, it enables earlier detection of diseases with better accuracy by simply having the capability to analyze complex sets of data (Poalelungi, Diana Gina, et al.). AI algorithms have also been better than trained medical professionals in tasks like the diagnosis of breast cancer and detecting skin lesions (McKinney, Scott Mayer, et al.; Esteva, Andre, et al.). For clinicians, AI can be helpful by completing routine tasks like summarizing patient histories and charting, which can improve the workload of the clinicians along with the amount of time they can spend directly caring for their patients (Rajkumar, S. Vincent.). AI has shown promise in the field of oncology, where it is capable of analyzing radiology data such as MRIs or mammograms, which has yielded better accuracy in

detecting early-stage cancers (Ahn, Jong Seok, et al.). In mental health care, AI is being trained on electronic health records (EHRs) to identify subtle warning signs of depression, anxiety, or suicidal ideation, often before the symptoms become clinically apparent (Shickel, Benjamin, et al. , Zafar, Fabeha, et al. “The Role of Artificial Intelligence in Identifying Depression and Anxiety: A Comprehensive Literature Review.” Cureus, Mar. 2024,). These predictive tools have the potential to transform how healthcare systems intervene, shifting the focus from reactive treatment to proactive prevention. In cardiology, AI is helping identify arrhythmias from ECG data (Nagarajan, Venkat D., et al.), while in neurology, it's being used to predict cognitive decline in patients at risk for Alzheimer's disease using a combination of speech data and brain imaging (Kenjeres, Sasa, et al.).

While these developments are promising, it is important for one to note that not every single AI advancement makes it to clinical use as it is important to distinguish an AI model from an AI system as an AI model is a statistical algorithm that is mainly used in controlled experiments as it typically performs better in research settings than in real-life situations because it has issues protecting patient privacy, and developing easily usable interfaces that clinicians can operate effectively in high-pressure environments like the hospital. When a model is performing well then it becomes an AI system which is a tool that can be fully deployed in a hospital or clinical setting.

This study is motivated by the observation that many AI systems in healthcare have either succeeded (De Fauw, Jeffrey, et al.) or failed (Jie, Zhou, et al.) due to critical design factors influencing their performance, safety and adoption. These past outcomes raise a central question: What would an ideal AI Healthcare system look like, and what lessons can we learn from its previous implementation into the medical field? This study aims to answer this question by doing an in-depth analysis of past success and failure cases. This analysis will also aim to discuss the design of an ideal AI system for healthcare.

2. Methods

This work compares two examples of AI systems: one that failed and one that succeeded in order to identify factors that led to shortcomings and breakthroughs of AI in healthcare. One example of each was examined in this study. This paper first looks at the AI System developed by Google DeepMind which analyzed retinal scans to improve the diagnostic accuracy of a wide range of diseases and was successfully integrated into clinical settings shortly after its development. On the other hand, this study also takes a look at IBM Watson for Oncology which was an AI System that was a major setback for the incorporation of AI within the field of healthcare. This system was a shortcoming due to narrow training data, lack of generalizability, and conflicting suggestions compared to those of trained professionals. Building on these examples, this study proposes an ideal AI system for healthcare with a focus on heart failure and diabetes. Heart failure and diabetes are significant conditions that affect millions of people worldwide. For example, an estimated 6.7 million Americans who are above the age of 20 currently live with heart failure and this number is only projected to increase (Groenewegen,

Amy, et al.). In a similar fashion, diabetes affects 589 million adults around the globe and this number is projected to only rise as time passes (Standl, Eberhard, et al.). A potential solution to lowering these concerning statistics would be the implementation of wearable devices such as smartwatches which yield potential in managing these complications. These devices allow for the constant monitoring of health data such as activity levels or heart rate, personal to each person who wears the device (Jafleh, Eman A., et al.). By utilizing personalized data tailored to each patient, healthcare providers can gain a detailed view of a patient's history and can make informed diagnoses with ease. The proposed AI will utilize these advancements by detecting chronic conditions like diabetes or heart failure before symptoms appear by making use of resources like EHR and wearable devices that can monitor heart rate and glucose such as an Apple Watch. By combining case study analysis with system design this study aims to provide insights that can be applied to create AI tools which can be employed in healthcare with trust and efficiency.

2.1. Success Case Study

When an AI model demonstrates consistency and quality performance, it can then be incorporated into a clinical setting, yielding benefits for both patients and healthcare workers. In 2010 Google's DeepMind developed a revolutionary AI system that utilized machine learning to analyze vast amounts of data to analyze 3D retinal scans and detect over 50 types of eye diseases with better accuracy than an ophthalmologist with years of experience could (De Fauw, Jeffrey, et al.). It was developed in collaboration with the leading healthcare institutions in both the US and the UK, and was trained on a diverse set of data that included vast amounts of retinal scans and images from clinical environments. One of the key drivers of its success was the high quality and diversity of the training data, which allowed the model to generalize well across different populations. Additionally, the DeepMind team placed strong emphasis on rigorous validation by testing the model against independent datasets and comparing its performance directly with that of experienced radiologists. It was found to predict conversion to exAMD and reach 80 percent sensitivity with a specificity of 55 percent (Yim, Jason, et al.). Another important factor was the involvement of clinicians throughout the development process, ensuring that the system would not only be accurate but also usable in real-world clinical workflows. Rather than functioning as a black box, the system was designed to be interpretable and to provide clear decision support, which increased trust and practical value in clinical settings. The success of DeepMind's project demonstrates that when AI systems are developed with robust data, rigorous testing, and collaboration with medical professionals, they can meet the demanding standards of clinical care and have a real-world impact.

2.2. Failure Case Study

Even though there are many successful stories like DeepMind's, not all AI systems can achieve their goals despite being designed with good intentions. A flawed diagnosis, or a wrong second opinion can lead to harm to the patient, or unnecessary procedures that take up time and

cost extra money. An example of a failure case would be IBM Watson for Oncology which had a goal in mind of providing assistance to oncologists by analyzing large volumes of literature to recommend personalized cancer treatments to every individual patient it took care of. IBM aimed to achieve this goal by combining natural language processing with expert knowledge to provide opinions on complex decisions related to oncology (Jie, Zhou, et al.). It intended to bridge knowledge gaps by analyzing the latest trends in medical literature, clinical trials, and guidelines in treatment. By doing this the system would provide clinicians with up to date information that they could use to support their decision-making for oncology patients. Another goal of the system was to provide personalized treatment plans that were tailored to each patient's genetic profile. By doing this IBM could enhance the effectiveness of its patient care and reduce potential errors. A further objective IBM Watson envisioned for its system would be the ability for it to democratize high-quality oncology care, potentially in resource-limited settings such as third-world countries, where patients often lack access to high-quality oncology care (Tyler, Christina R. Steadman, et al.). Beyond healthcare, IBM also had a vision for Watson to be a leader in AI applications, showcasing the transformative potential of cognitive computing and establishing IBM's position at the top in terms of AI integration into healthcare.

After a few years the system began to face some serious criticism as its decisions were beginning to yield concerning results. These results were due to the fact that IBM Watson for Oncology was trained on a narrow set of data so it was ill-prepared to provide results that were generalizable to a bigger population because the data was coming from just one hospital. Another cause of Watson's failure would be that the goals from the start were always too high as IBM's aggressive marketing strategies exaggerated the true capabilities that the system had. This created unrealistic expectations from customers which led to the trust in the product eroding quickly. Watson also failed to make their system user-friendly for clinicians as it had a reliance on manual data entry along with having an interface that was difficult to navigate which led to it disrupting clinical workflows instead of improving them (Keikes, Lotte, et al.). IBM Watson for Oncology also had a lack of ability to adapt to variation as it struggled to accommodate differences in resource availability and cultural practices across different hospitals, so in diverse settings the system struggled to succeed. Another weakness within the system was a lack of transparency which was due to the high expectations that had been placed on it from the very beginning. With the pressure to yield tremendous results, IBM had to resort to using hypothetical cases and selective data to demonstrate the "capabilities" the system had which raised ethical red flags and led to further distrust amongst customers (Staff, Ahcj.). This unsuccessful operation came to an end in 2020 when IBM Watson began to scale back its operations. By 2022 it was sold off to Francisco Partners which ended its nearly 10-year period of disaster.

3. Results

Designing an Ideal AI System in Healthcare

Looking back at these past successes and failures, this study proposes an ideal early detection AI-based system that is specifically designed to identify those at risk for heart failure, and diabetes. The system uses EHR data and wearable signals which track the heart rate and glucose of the patient to identify whether a patient has a strong likelihood of developing these conditions before symptoms appear on the surface (Ng, Kenney, et al.).

Building on its ability to identify patients with a heightened risk of heart failure or diabetes, this system is capable of making a personalized treatment plan specific to every patient it takes care of. The system utilizes data such as patient history, genetic data, and prior real-world outcomes to estimate the effectiveness and risks of every treatment option for each patient. The system is trained on datasets that represent diverse patient populations and clinical environments, which helps to prevent biases that arise from narrow training data, as seen in the case of IBM Watson. Validation should extend beyond internal testing, incorporating independent external datasets. For example, DeepMind's success was tied to careful testing against independent clinical data and comparison with expert performance.

The system then makes recommendations to medical professionals as to the most appropriate treatment options.. The system is developed in close collaboration with healthcare professionals, ensuring its outputs align with medical expertise and clinical realities. The system supports clinician judgment by offering evidence-based recommendations that can be reviewed and modified by medical teams. This approach enables care plans that are not only evidence-based but also tailored to the individual's clinical profile, lifestyle, and treatment preferences, potentially improving adherence and long-term outcomes. Once an individualized care plan has been generated, the system care coordination component ensures that its recommendations are implemented effectively. This can be done by enhancing communication across the healthcare team it is working with. This component will also deliver personalized reminders for the patient for upcoming meetings or tasks like taking a pill via a mobile app (Huang, Chu-Ya, et al.). Another strength of this AI system would be its ability to improve health literacy for the general population it takes care of and educate them on their own diagnoses in plain, easy-to-understand language. This system does this through a chatbot in a mobile app, simulating a conversational interaction with their physician. The system also possesses the capability to support the general population as a whole by identifying emerging trends such as drug resistance patterns, infectious disease outbreaks, and shifts in chronic disease incidence via advanced analytics and anomaly detection algorithms. These insights are communicated to regional health officials, who could then intervene and make proper use of resources to stop these outbreaks from becoming drastic (Villanueva-Miranda, Ismael, et al.). Another way the system could make a difference is through how the patients, doctors, and nurses can interact with it to ensure smooth communication, proper interventions when necessary, and coordinated care that improves patient outcomes while enhancing the quality of life for the healthcare team. Doctors can review the AI-generated diagnoses and treatment plans to make final decisions, patients can receive explanations and reminders, and ask questions via chatbot, and nurses can make use of system alerts to manage follow-up meetings and coordinate care (Khosravi,

Mohsen, et al.). Another vital component of this system is its regulators which will allow it to audit model decisions and monitor performance through dashboards that provide insights into its own accuracy and bias. These regulators then review reports to verify that the system complies with guidelines and meets its established standards to ensure patient safety and maintain fairness (Abulibdeh, Rawan, et al.). Additionally, the system can explain the reasoning in a way that is comprehensible to clinicians and patients, which prevents the erosion of trust that contributed to Watson's failure. Together, these AI-driven components from care coordination to personalized treatment recommendations have the potential to make a system that can transform healthcare by improving early detection, enhancing treatment effectiveness, and improving the quality of life for healthcare teams across the globe.

4. Discussion

The previously proposed AI system aims to address many of the limitations observed in past failure cases such as IBM Watson. It attempts to do this by placing a strong emphasis on diverse data integration, rigorous validation from trusted institutions, and collaboration with elite clinicians to ensure that it will not repeat previous mistakes. This system will utilize EHRs and wearable device data to detect early signs of chronic conditions. By utilizing multiple sources of data the system will be able to provide a more accurate decision-making process to clinicians while improving quality of life within healthcare settings.

Despite these potential advantages from building off past failures, this proposed system could still have flaws. An example of a challenge this system could face would be noisy data. Wearable data may be inaccurate at times due to step counts or heart rate measurements being off due to a device running out of battery or the user forgetting to wear the device. This leads to inaccuracy in data and poses a threat to the ability of the system to operate with consistency (Falter, Maarten, et al.). Another critical aspect in the successful development of this system would be collaboration with top healthcare professionals as many of the failures like those observed in the IBM case were due to poor collaboration between healthcare teams and the system. A potential fix to this problem would be having clinicians review whether the decisions the system makes would be the best in the particular context it is being used in. This approach would enhance the trust that clinicians have in the AI while improving patient experiences at the same time. This would ensure that the system is not a total replacement of judgment, but rather a tool to aid the judgment of trained medical professionals. While challenges do remain, this approach provides a blueprint for building AI systems in the future that are trustworthy, ethical, and beneficial for all parties.

5. Conclusions

In conclusion, AI-based systems have the potential to yield tremendous benefits in the field of healthcare if properly developed with diverse data sets, including clinicians in the development loop, and proper integration into clinical settings. Building on these past lessons, the proposed AI system focuses on detecting conditions like heart failure and diabetes, utilizing

wearable device data and EHRs to come up with care plans personalized to each patient. By utilizing frameworks for transparency and decision-making the system ensures trustworthy care and communication between healthcare teams and patients. By learning from past experiences, AI in healthcare can be a trustworthy and impactful tool that can significantly improve the quality of life within a clinical setting, when implemented correctly.

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The Therapeutic Function of Greek Tragedy: Trauma, Catharsis, and Healing in Euripides' Herakles By Yukun (Kingsley) Du

Abstract

The scholarly literature on the therapeutic function of theater—especially as it operates in Ancient Greek tragedy—is surprisingly thin.. It is only with the groundbreaking work of Jonathan Shay, that ancient tragedy has been understood to function as a form of collective therapy, allowing individuals to process emotion, confront social tensions, and engage in healing from psychological trauma.¹

In his *Poetics*, Aristotle first explicitly linked tragedy with the catharsis of the central emotions it inspires: pity and fear. This essay will focus on Euripides' *Herakles*, a play that largely substantiates Shay's theory, while offering nuance and depth to Aristotle's theory of catharsis. Although Aristotle had established catharsis on the concept of elicitation and purgation, Euripides redefines catharsis in *Herakles* as a process that is rooted in dialogue and connection. His portrayal of Theseus and the vital role that language plays in this play highlights that recovery from trauma requires restoring one's capacity to communicate and be heard in a community.

In addition, *Herakles* reveals that, despite the association the Greeks had made between trauma and physical wounds, they possessed a nuanced understanding of psychological distress, as well. *Herakles*' violent actions lead to his profound internal suffering. This play reflects themes of guilt and anguish with language that resonates with contemporary discussions of trauma, showing Euripides' deep appreciation for drama's ability to act as a healing *pharmakon*, or medicine.

Tragedy, Trauma, and Catharsis

Ancient Greek theater, specifically tragedy, has its roots in the cult of Dionysus, the god of festivity, wine, and theater. In his *Poetics*, Aristotle speculates that tragedy first began as "mere improvisation" on the dithyrambic hymns sung in honor of Dionysus.² Descriptions of Dionysus' encounters with humans consistently portray him as a force of transformation, with the power to induce madness or ecstasy, whether through alcohol or dramatic performance.³ The presence of Dionysus meant the alteration of identity, metamorphosis of the man, a state of metamorphosis in which people became "ecstatic," "not in [their] right mind," or "full of god."⁴

¹ Jonathan Shay, *Odysseus in America : Combat Trauma and the Trials of Homecoming* (Scribner, 2002), 152-153.

² Aristotle, *Poetics*, trans. S. H. Butcher (2008), Part IV.

³ Laszlo Versényi, "Dionysus and Tragedy," *The Review of Metaphysics* 16, no. 1 (1962): 84, <http://www.jstor.org/stable/20123925>.

⁴ *Ibid*, 85.

Since Dionysian possession meant becoming a vessel for the divine, the Greeks regarded this madness as “a noble thing... [that was] superior to the health of mind.”⁵

To participate in tragedy, whether as the chorus, actor, or spectator, was to temporarily be possessed by roles, stories, and emotions that both destabilized and reconfigured oneself. The disassociative nature and ecstatic potential of theater makes it a fertile catalyst for catharsis.

Two key terms are important in understanding the psychological impacts of Greek tragedy: trauma and catharsis.

Catharsis (κάθαρσις) was originally a medical term referring to the process of purification and purgation.⁶ Aristotle argues that tragedy achieves κάθαρσις by evoking emotions such as pity and fear.⁷ As audiences experience these intense feelings, they can more easily process their personal issues, leading to emotional relief. In Aristotle’s understanding, theatre serves as a kind of emotional purgative, cleansing and purifying actors and spectators of their trauma.

For the Ancient Greeks, ‘trauma’ (τραύμα) was primarily used to describe physical wounds.⁸ In contrast, the modern usage of trauma typically refers to lasting and severe mental or emotional damage, which results from an unusual event.⁹ Yet, tragedy shows that Greeks recognized psychic injury. Indeed, its depictions of anguish, grief, and other states of extreme mental distress closely resemble modern discussions of trauma.

Herakles

Euripides’ Herakles is one of antiquity’s most striking dramatizations of psychological trauma that results from catastrophic events. In this way, it closely parallels contemporary understandings of trauma. The play’s eponymous character suffers a catastrophic mental collapse as a result of the traumatic aftereffects of combat, while also reflecting on how violence and its repercussions can negatively affect combatants and non-combatants. Performed before a civic audience, Herakles “provided opportunities for the city’s inhabitants and visitors to reflect upon war... trauma, [and] grief, and commemoration in a collective social setting.”¹⁰

Herakles depicts the homecoming journey of the Greek hero Herakles (known in Roman mythology as Hercules). According to tradition, Herakles was the son of Zeus and Alcmene, the

⁵ Plato, *Plato's Phaedrus*, trans. Harold N. Fowler (London: Harvard University Press, 1925), 244c-d, <https://www.perseus.tufts.edu/hopper/text?doc=Perseus%3Atext%3A1999.01.0174%3Atext%3DPhaedrus%3Asection%3D244d>.

⁶ "Catharsis," in *Encyclopedia Britannica*, last modified July 19, 2025, <https://www.britannica.com/art/catharsis-criticism>.

⁷ Jacob Bernays and Peter L. Rudnytsky, "On Catharsis: From Fundamentals of Aristotle's Lost Essay on the 'Effect of Tragedy' (1857)," *American Imago* 61, no. 3 (2004): 319, <https://www.jstor.org/stable/26304859>.

⁸ Gerasimos Kolaitis and Miranda Olff, "Psychotraumatology in Greece," *European Journal of Psychotraumatology* 8, no. sup4 (2017): 1, <https://doi.org/10.1080/20008198.2017.1351757>.

⁹ Erika L. Weiberg, *Demanding Witness: Women and the Trauma of Homecoming in Greek Tragedy* (New York: Oxford Academic, 2024), 5.

¹⁰ *Ibid.*, 18.

granddaughter of the Greek hero Perseus.¹¹ Zeus' affair with Alcmena enraged his wife Hera, so Alcmena, in an attempt to placate Hera, named her son Herakles, which means the "glory of Hera."¹² This gesture only further arouses the wrath of Hera, who next sends two snakes into Herakles' crib—which the infant hero strangles to death in short order. Realizing that Herakles's strength made killing him virtually impossible, Hera resolved instead to make him suffer.

When Herakles reached adulthood, he married Megara, daughter of King Creon of Thebes. The couple had three sons, whose prosperity stoked Hera's hostility. Hera afflicted Herakles with madness, pushing Herakles to kill his entire family with his own hands. Wracked with guilt, Herakles consulted the Oracle of Delphi to learn how he may atone for the murders. The god instructs him to serve King Eurytheus and complete his famous Twelve Labors, seemingly destined to kill him or any man who attempted them.

Euripides departs from the traditional chronology of the myth, most notably in the placement of Herakles' madness. In the standard myth, Herakles' madness leads to his twelve Labors as a form of atonement. In Euripides' version, Herakles' madness strikes after he completes his labors and returns to Thebes. Thus, this deviation from the standard plot of the myth reframes the labors as a source of trauma. The play, then, is not just a celebration of heroism but a drama of psychological resilience. The tragedy centers on Herakles's struggle to come to terms with his guilt.

Euripides' Herakles induces catharsis in the audience by invoking the theme of nostos (νόστος), or homecoming. These transitions from war to normal civilization were seldom peaceful. Works, such as Homer's *Odyssey* or Euripides' *Herakles*, used the nostos narrative pattern to convey the devastation of war and its consequences for families and social life as warriors struggled to reintegrate into family and civic life after a lengthy absence.¹³ These effects would have been familiar to Greek theater audiences, as warfare was a regular occurrence and men were often away on campaigns for months or years at a time.¹⁴

In *Herakles*, Euripides demonstrates that the journey back home is not just a transition physically, but also an emotional and psychological reckoning with one's previous actions and their consequences. Herakles' disposition towards violence in the beginning of the play are indicative of his trauma. His description of the instability of his mind and his loss of self-control, culminating in the murder of his family, show how powerfully and destructively the battlefield can linger in the warrior's psyche. While the murder of his family for Herakles is the result of his trauma, it is also in itself trauma. When he recovers from his madness, the anguished recognition nearly breaks Herakles, who eventually copes with the resulting trauma through self-reflection, encouraged by Theseus.

¹¹ Editors of Encyclopaedia Britannica, "Heracles," in Encyclopaedia Britannica, last modified March 13, 2025, <https://www.britannica.com/topic/Heracles>.

¹² Joshua J. Mark, "The Life of Hercules in Myth & Legend," in World History Encyclopedia, last modified July 23, 2014, <https://www.worldhistory.org/article/733/the-life-of-hercules-in-myth--legend/>.

¹³ Peter Meineck and David Konstan, *Combat Trauma and the Ancient Greeks* (Palgrave Macmillan, 2014), 9.

¹⁴ Weiberg, *Demanding Witness*, 16.

Herakles' Trauma as Context

Herakles' trauma manifests on emotional, psychological, and physical levels. Euripides thus establishes Herakles as a man pervaded by suffering and resulting trauma. Subsequently, Euripides employs language to add further nuance to his unique suffering, using diction that ultimately destabilizes the heroic ideal of Herakles and complicates the tragedy's cathartic effect.

Perhaps the most vivid symptom of Herakles' trauma is his inclination toward violence. Upon returning to normalcy from his traumatic experience in the Underworld, his disorientation and exhaustion erupt in fantasies of grotesque brutality, ultimately driving him to insanity. The strain of completing the Labors has irrevocably altered his psyche, causing him to favor violence in nearly all contexts. For example, after learning that a usurper named Lycus has taken control of Thebes and is threatening to kill Herakles' family, Herakles vows:

“I will first go and utterly destroy the house
of this new tyrant [turannos], ripping his unholy head
and hurl it to the hungry dogs as prey.”

Eur. H. 566-568¹⁵

Circumstances notwithstanding, Herakles's reaction is overwhelmingly violent. It exceeds mere retribution. The actions he imagines—destroying a home, tearing off his enemy's head, and feeding it to wild dogs—are grotesquely brutal and far exceed what is necessary to restore order according to typical standards of restorative justice. The specificity of Herakles's descriptions reveal the intensity of his anger: he is not content merely to kill Lycus, but wishes to make him suffer as much as possible. In addition, his fixation on methods of killing Lycus show how thoroughly violence has captured his thoughts. The Labors have not purged Herakles's violent impulses but have left him consumed by them.

In one striking passage, Herakles declares that he will continue his campaign of vengeance until “all Ismenus is choked with the dead / and Dirce rolls her silver tide with blood discolored.”¹⁶ The references to death and blood are unrepentantly savage, conjuring obscenely vivid scenes of slaughter and desecration. The brutality is made even more vivid by the inclusion of Lycus's wife, Dirce; Herakles is so obsessed with violent retribution that he is utterly indifferent to the collateral damage of his revenge. Ismenus and Dirce, furthermore, are water deities associated with serenity and renewal.¹⁷ Their imagined pollution with corpses and blood expands Herakles's wrath beyond the human domain to the natural world to that of the divine.

Herakles' thoughts of brutality are accompanied by signs of disorientation and emotional instability.

¹⁵ Euripides, *Herakles*, trans. R. Potter, ed. Casey Dué and Mary Ebbott, Line 566-568, <https://www.uh.edu/~cldue/texts/herakles.html>.

¹⁶ *Ibid.*, Line 572-573.

¹⁷ William Smith, *A Dictionary of Greek and Roman biography and mythology.*, 1873, <https://www.perseus.tufts.edu/hopper/text?doc=Perseus:text:1999.04.0104:entry=ismenus-bio-1>.

As on tumultuous waves and tempests my mind [phrên]
whirls and heaves...

Eur. H. 1091-1092

Herakles is beset by confusion and madness. The comparison of his mind to a stormy sea conveys the force of his inner turmoil, suggesting that he is no longer capable of rational thought. That this passage occurs after Herakles has slaughtered his own family in a fit of madness underscores the continued, acute psychological impact of that violence. This turmoil affects not only his thoughts but also his language. Coherent dialogue gives way to fragmented dialogue or silence, with others frequently narrating his descent into madness and irrationality. Euripides signals that trauma erodes not just reason but speech itself as the hero becomes linguistically and psychologically displaced.

Language in Herakles' Trauma

The immediate cause of Herakles's affliction is Lyssa, the goddess of madness, who attacks him on Hera's orders.¹⁸ As Lyssa takes over his mind, she simultaneously takes over the role of narrator in Euripides' Herakles, describing Herakles' appearance, as follows:

In silence his distorted Gorgon eyes,
his breathing is not balanced [sôphrôn]: like a bull
Dreadful in the assault he roars, and calls the Stygian Furies,
he howls with noisy fury, like dogs rushing on the hunt.
I will dance to you even more quickly and I will play the flute of terror.

Eur. H. Line 867-871¹⁹

Here Herkules is thoroughly dehumanized, described in a series of monstrous forms—a bull, a Gorgon, a dog. These creatures lack the capacity for reason and self-conscious action, thus exemplifying Herakles's lack of rational, self-possession. In particular, the likening of Herakles's eyes to those of a Gorgon directly marks him as a monster.²⁰ Notably, the moment in which Herakles gets taken over by Lyssa marks one of the first major moments in which he no longer actively communicates via language. The audience subsequently view Herakles from the outside, distanced and dehumanized. By creating this separation between the audience and main character, empathy is largely eliminated for Herakles' plight, and the actions he commits become all the more gruesome, painful, and pitiful.

This alienation culminates in Herakles' murder of his family. The Messenger who narrates these atrocities, recounts the final plea of one of Herakles's sons. After witnessing the killing of his brother with an arrow, the boy runs to embrace his father, pleading for mercy: "O

¹⁸ Karelisa Hartigan, "Euripidean Madness: Herakles and Orestes," *Greece and Rome* 34, no. 2 (1987): 126, <http://www.jstor.org/stable/642941>.

¹⁹ Euripides, Herakles, 867-871.

²⁰ Ibid, 867.

dearest father, listen, do not kill me, / I am your, your child, you are not killing one of Eurystheus.”²¹ Herakles, still in the grip of madness, responds only with a “Gorgon-glaring eye.”²² The boy’s attempt to break through to Herakles by reminding him of their familial bond goes utterly unnoticed. Herakles’s mind is too clouded by vengeance and anger; he is incapable of seeing his own family as anything other than enemies.

Herakles’s madness alters how he perceives those around him. It warps his sense of human connection, causing him to dehumanize others, mirroring his own dehumanization:

And, as the boy pressed too close to let the arrow fly,
as one smites iron on the anvil, on his golden tresses
He dashed the fatal club, and crushed the bone.

Eur. H. 992-993²³

The familial relationship between Herakles and his son vanishes in this moment. Having been introduced to the audience as a pleading child, the boy is now reduced to a mere collection of golden hair and bones. There is also the comparison of the boy to an anvil, an inanimate object, and one meant to create hard iron tools and weapons. Herakles’s collapse of reason is also evident in the extreme, reflexive savagery with which Herakles carries out his killings. When the boy runs too close to be shot with an arrow, Herakles unhesitatingly switches to his club to smash him to death. The sheer brutality of the act, combined with the son’s textual dehumanization, is yet another blurring of the the boundaries between humanity and object, as

When zooming out to look at the entire scene altogether, Herakles’ inability to drive the narrative cements his trauma. The only people who do speak as Herakles commits his atrocious acts against his family are Iris, Lyssa, and the chorus. At the climax of Herakles, we do not hear the title characters’ words or his internal thoughts; he has succumbed to madness completely. Language—or here the lack thereof—once again, serves as a vital tool for Euripides to reinforce the causal impacts of trauma. This narrative shift away from Herakles is yet another way in which Euripides adds more nuanced dimensions into Herakles’ trauma and how he will achieve catharsis later in the play.

Herakles’ Monologues

Murdering his family severely intensifies Herakles’s trauma. Unlike the Twelve Labors, where his suffering was channeled outward against external enemies, this act turns his torment inward. **This internal torment incurs a breakdown in dialogue itself.**

When Herakles first awakens from his madness, in lines 1110 to 1145, Herakles is able to speak coherently with his father Amphytrion. Though devastated by the sight of his dead family, he has not yet realized that he is their killer. The madness sent upon him by Lyssa has also

²¹ Ibid, 988-990.

²² Ibid, 990.

²³ Euripides, *Herakles*, 992-993.

deprived him of the memory of his actions. When the full truth of his actions dawns on him, his speech is immediately compromised and becomes fractured by guilt:

This last bloody labor [ponos] I dared (Wretch that I am!),
the murder of my sons; I have crowned my house with ills.
I have come to this point of necessity, at my beloved [philos]
Thebes I cannot dwell. Where would I stay?
Eur. H. 1279-1282²⁴

Herakles knows that he can no longer live with himself, nor with others in the city of Thebes. Fixating on his actions, he ironically characterizes the slaughter of his family as the last of his labors. Yet, what was once a source of heroism—his capacity for violence—has now become the cause of his catastrophic downfall. In the aftermath, his speech devolves into disjointed monologues—rambling, repetitive, and unable to sensibly sustain exchange with others. He comes like the beasts or monsters he was compared to earlier. His language, once a marker of his civilized, human state, comes apart to mirror his psychic disarray.

There is a salient lack of conversation at the most intense point of Herakles' trauma. Stuck in a state of irrational frenzy, Herakles's mind jumps from topic to topic, as he relates his fear the public judgement:

Should I seek refuge in another state [polis], then,
where malignant eyes would scowl on me when known,
and tongues goad me with bitter reproaches:
'Is this not the son of Zeus, who once killed his sons
and wife?' Then chase me out with curses on my head.
Eur. H. 1286-1290²⁵

Herakles imagines how others will perceive his actions, and his mind ricochets between fear, shame, and exile. Knowing he will be unable to live peacefully in Thebes, Herakles understands he must relocate, but fears that his infamy will follow him. He also understands that the moral magnitude of the murders will be all the greater due to his lapsed status as a hero and demigod. In the ensuing sixty lines, Herakles vents a torrent of self-condemnation as he considers the horror of his actions and the trauma that he has inflicted upon himself. By refusing to engage in dialogue with Theseus, resolving instead to combat his friend's suggestions with abrasive and long-winded monologues, Herakles retreats entirely into isolation and self-loathing.

The trauma Herakles feels, which has been clearly established by Euripides, has shattered the very foundation of language and communication. Consistently, as this play progresses, the audience becomes aware of the continuous breakdown of language—the shared speech that binds

²⁴ Ibid, 1279-1282.

²⁵ Euripides, Herakles, 1286-1290.

individuals to a community and was key to the development of the dithyramb to tragic theater—which ultimately makes it impossible for Herakles to be involved in civic life.

Recovery and Catharsis Through Language

Instead of the traditional theories that explain the catharsis of Euripides' Herakles, many of which are based in Aristotle's statements in his *Poetics*, language—and its breakdown as a result of trauma plays a pivotal role in Herakles. Indeed, it is the language of Theseus that expresses his steadfast compassion that reintroduces Herakles into the language of belonging:

I hate those who let the impression of a friend's [philos]
kind deeds [kharis] fade from their heart; and they, who wish to share
His prosperous gale, but will not sail with unfortunate friends [philo].
Stand up, unveil your wretched head
And look upon us. Whoever of mortals is noble,
He bears the calamities sent by the gods and does not refuse.

Eur. H. 1226-1228²⁶

A hundred lines earlier, Herakles had resolved to commit suicide as a self-imposed punishment. But with the support of Theseus and his father, Amphitryon, Herakles chooses to live, despite his immense guilt. The “saving grace of friendship [philia]” changes his mind.²⁷ In the above passage, Theseus twice invokes the language of friendship (philos, philoi), presenting it as an immutable bond that withstands suffering. Theseus' actions to comfort Herakles, including his refusal to abandon his side, does not fully purge Herakles' guilt, but reframes it as a shared burden.

As a true friend, Theseus repays Herakles' kindness, offers counsel, and remains loyal—even in the face of divinely-imposed calamities.²⁸ By repeating and demonstrating these values, Theseus transforms the play from one dominated by violent monologues to one informed by dialogic conversations. He creates a bond, which ultimately restores Herakles' capacity to speak and be heard. Theseus first approaches Herakles in a way that mirrors the form of Herakles' monologues, as Theseus speaks expansively to convince Herakles to maintain his normal life. As he transitions into dialogue with Herakles, this reciprocated exchange of ideas sets up the basis for Herakles' eventual catharsis. Effectively, Herakles' recovery is facilitated by Theseus' language of steadfast support, thus demonstrating that healing does not depend on the purging of emotions, but rather the restoration of one's capacity to speak and be heard within a community.

Redefining Catharsis with Herakles

²⁶ Ibid, 1223-1228.

²⁷ Sonia Petsinidis, "Resilience and Euripides' Heracles," *Humanities* 10, no. 1 (2021): 44, <https://doi.org/10.3390/h10010044>.

²⁸ Euripides, Herakles, 1224 / 1313.

According to Aristotle, catharsis in tragedy is achieved through the arousal of painful emotion in the audience: the “eliciting of emotions”, he writes, is “a means of purifying related bad memories.”²⁹ Characters onstage act as proxies for the audience, and their emotional purgation stimulates a similar process in the spectator.³⁰ Aristotle gives particular attention to the emotions of pity and fear.³¹ In many ways, Herakles confirms Aristotle’s theory of catharsis. The eponymous hero’s slaughter of his wife and sons induces fear through the violent spectacle of god-imposed madness, then pity as Herakles regains his senses and sees the ruin he has caused. Aristotle’s theory relies on fostering empathy and connection so that spectators can use the dramatic characters to reflect on their own lives in a new light. Moments such as these give tragedy its emotional power. They present recognizable forms of suffering, such as Herakles’s trauma, in a way that allows spectators to “relive them passively.”³²

Herakles also fits well Aristotle’s conception of the ‘ideal’ tragic figure: not “eminently good and just,” but someone who suffers a downfall due to “error and frailty” rather than any inherent “vice or depravity.”³³ Herakles did not commit his slaughter on purpose; while Herakles’s actions were intentional up to a point, he was under the control of Lyssa when he committed the actual murder of his family. Therefore, Herakles need not bear the full burden of responsibility for his actions, in the same way that in a modern court of law an “insanity defense” can lessen the gravity of a defendant’s punishment.

Yet, in spite of Herakles’s close adherence to Aristotle’s model, Euripides complicates and expands upon his traditional model of catharsis. In Herakles, catharsis is not merely achieved through the mechanics of emotion and characterization, but also through active conversation. Euripides offers a profound reimaging of catharsis as a process of bonding through language rather than mere emotional purgation. Herakles demonstrates how trauma can completely shatter one’s capacity for reciprocal communication, which makes participating in a communal life essentially impossible. Had Theseus not intervened in monologue and then dialogue, Herakles would have been left to fester in a cesspool of his own guilty thoughts. Their interaction stresses that healing is not dependent simply on the purging of emotions. Rather, Herakles’ journey to recovery relies on the restoration of his ability to speak and truly be heard in a community that empathizes and understands his suffering.

Euripides’ redefinition of catharsis challenges and expands Aristotle’s traditional theory. By creating a particular emphasis on the communal and linguistic dimensions of healing in Herakles’ journey, Euripides raises extremely unique insights into aspects of trauma recovery that remain relevant in the status quo.

²⁹ Stefan Meisiek, “Which Catharsis Do They Mean? Aristotle, Moreno, Boal and Organization Theatre,” *Organization Studies* 25, no. 5 (2004): 797, <https://doi.org/10.1177/0170840604042415>.

³⁰ John Gassner, “Catharsis and the Modern Theatre,” in Aristotle’s “Poetics” and English Literature, pp. 109-10. Originally Barrett H. Clark, ed. *European Theories of Drama*, rev. Henry Popkin (New York, 1965), 514-518.

³¹ Aristotle, *Poetics*, Part VI.

³² Meisiek, “Which Catharsis,” 797.

³³ Aristotle, *Poetics*, trans. S. H. Butcher (2008), Section VIII.

Thus, in Euripides' Herakles trauma is not just a wound that needs to be purged, it is a rupture in the shared language of belonging). Herakles challenges the traditional, individualistic journey of purging emotions, which Aristotle posits, instead focusing on the collective journey to emotional relief brought about by sharing language with a community. This sharing serves not only to validate personal feelings, but also to reinforce the idea that suffering is universal. Catharsis is not simply a state that can be achieved one individual at a time, much less forced onto a group of people simultaneously. Instead, it is more about building up a strong collective that is able to provide unwaveringly strong support to everyone through language that validates individual suffering. If Theseus were not by Herakles' side, he would never have been able to recover from his trauma. In fact, Herakles himself stresses the importance of this type of communal bond: "Unwise is he, who prefers wealth or power / to the rich treasure of a good [agathos] friend [philos]." ³⁴

On a side note, dramatic art is the perfect medium to achieve catharsis through the communal sharing of language. One of the most important aspects of theater is its interdependent relationship with community. The rituals that are inherent to theater, such as the act of gathering together, and the shared act of witnessing and emoting as an audience, all work together to create a safe space for vulnerability—for venting the pain of trauma. In fact, Euripides challenges us to view theater not simply as an expression of emotions, but rather as a tool to rebuild social connections. This broader conception of the therapeutic potential of art has important implications for how we design and evaluate arts-based interventions for trauma survivors, such as Bryan Doerries' Theater of War organization, which we will discuss in the conclusion of this essay.

Ultimately, Euripides' Herakles reminds us of the fundamental importance of dialogue, connection, and shared growth in the healing process. Building upon and, indeed, challenging Aristotle's theories of trauma recovery, Euripides shows that recovery depends on the reweaving of language within a community—one conversation at a time. Herakles could not fully recover until he reestablished his place within his community through language and renegotiated his relationship with other people.

As we continue to grapple with the challenges of supporting individuals impacted by trauma, Euripides serves as a powerful corrective to simplistic models of recovery that focus solely on individual symptom reduction. The communal nature of catharsis as redefined in Herakles speaks to the limitations of individualistic approaches to mental health that have dominated Western psychology for much of the 20th and 21st centuries. People cannot feel safe alone, and they cannot mourn and make meaning alone". Herakles anticipates this insight by centuries, suggesting that healing from trauma requires not just individual emotional processing but the restoration of one's capacity to speak and be heard within a community.

Modern research has shown that traumatic experiences can disrupt language processing and communication abilities, making it difficult for survivors to articulate their experiences or connect with others. This makes a solution that addresses social integration and relational repair

³⁴ Euripides, Herakles, 1425-1426.

all the more important. By focusing on the linguistic and communal dimensions of catharsis, we can better understand how Greek tragedy functioned as a form of cultural therapy that went beyond individual emotional regulation to address the social dimensions of suffering. The most transformative form of therapy may be the simple act of listening and being listened to, of speaking and being heard, within a community that values and sustains us all.

Applications

Aristotle's concept of catharsis as augmented by our understanding of the role of language in trauma recovery gleaned from Euripides's *Herakles* has tangible, modern applications. In addition to Jonathan Shay's clinical work, which has stressed the importance of modern warriors to train together, enter danger together, and come home together, so that they can recover from trauma in a communal setting, several projects aim at using tragic theater directly to help modern veterans.

Peter Meineck has written extensively on the connections between Greek tragedy and modern combat trauma. As Meineck notes, "around 300,000 Iraq and Afghanistan veterans are likely to suffer from some form of Post Traumatic Stress Disorder."³⁵ His *Aquila* theater has served veterans for nearly thirty years, offering workshops post-performance so that veterans can compare their experience with war-induced trauma to those of the ancient state. In addition, Bryan Dorries, with his Theater of War Productions, have included combat veterans directly in theater productions—as the ancient Athenians did twenty-five centuries ago—to help modern warriors heal from trauma. Should the cathartic model of Euripides prove helpful, we may encourage even greater healing among these populations through greater attention to the linguistic and dialogic dimensions of healing highlighted in *Herakles*.

³⁵ Meineck and Konstan, *Combat Trauma*, 8.

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Briquette Manufacturing from Agricultural Residue: A Sustainable Energy Solution for Rural India By Diya Mittal

Abstract

This paper explores the feasibility and implementation of briquette manufacturing from agricultural waste in rural India, with a focus on Adilabad, Telangana. The objective is to present a sustainable solution that addresses pollution, waste management, and rural income generation. Through process analysis, equipment requirements, and economic viability studies, this paper highlights the potential for decentralized energy alternatives in India's agricultural heartlands. (Vaish et al., YEAR) (Lan et al., YEAR)

Introduction

The root of the problem is the fact that alongside increasing energy demand in India there is also rising environmental pollution which leads to a dilemma between the . This is an especially prevalent issue in rural areas as there is lack of access to clean and affordable energy, with many communities still depending on traditional fuels like firewood or dung. These fossil fuels produce multiple harmful effects: health because of indoor pollution, deforestation and carbon emissions.

India produces over 500 million metric tonnes of agricultural waste every year, when farmers don't know how to dispose of this waste, the most common practice is to burn it in the open air. However this causes severe air pollution and is unsustainable. This presents a major missed opportunity. What if this waste could be transformed into clean, affordable fuel? (Monish Vijay Deshpande et al., YEAR) Biomass briquetting is the process of compressing agro-residue into solid fuel. It is a very efficient way to get rid of the waste from farming as briquettes are low-cost, eco-friendly, and can be used by industries, institutions, and households alike. They help reduce dependence on fossil fuels while also offering farmers a way to earn from agricultural by-products.

This project began as a personal exploration during my summer break. During a visit to Adilabad Telangana, I noticed how much agricultural residue was left unused or burned. That observation sparked my interest in alternative energy solutions as I have seen firsthand how much agricultural residue is wasted.

This paper aims to provide a comprehensive but accessible guide to setting up a briquette unit—from raw material selection to marketing—while showing how this model can support sustainability, rural employment, and clean energy in India.

Background and Context

Adilabad also known as the white gold city is a district in northern Telangana and is widely known for its contribution to the cultivation of cotton in India. Apart from cotton a variety of crops are produced in Adilabad including wheat and rice, due to such a large amount of production there is also a significant amount of waste residue that is left behind from these

crops. This waste residue is going to be the main focus of this paper, in order to discard this waste it is a common practice to burn all the waste material including cotton stalks, rice husks and wheat straw. However there are multiple concerns with this practice due to the fact that it is extremely harmful for the environment. Each ton of crop residue approximately leaves up to 1400 kg of CO₂, 58 kg of CO, 11 kg of particulate matter, 4.9 Kg of NO_x and 1.2 kg of SO₂ this leads to air contamination, respiratory diseases, soil degradation, groundwater depletion and overall significant environmental harm.

Briquette manufacturing provides a wonderful opportunity to convert this agricultural waste into renewable energy production in the form of biomass briquettes. The process starts off with compressing loose biomass into dense blocks of fuel, this is a simple and sustainable method to deal with waste management and environmental problems that exist in Adilabad. How it works is that feedstock such as cotton husk and rice stalks need to be pressed into a briquette form with manual low-pressure presses or semi-automated screw extrusion systems. Proper pre-processing—such as reducing moisture content to around 12–14% and grinding the biomass to particle sizes under 3 mm—has been shown to significantly improve briquette durability, calorific value, and combustion efficiency. Additionally with compaction techniques their densities often exceed 1000 kg/m³ and caloric values between 12 and 18MJ/kg.

There have been many technical trials conducted in multiple regions of India including Andhra Pradesh and Maharashtra. In Andhra Pradesh cotton stalks were successfully converted into fuel blocks that are suitable for industrial use. On a national scale the amount of agricultural residue produced in India is extremely huge due to the fact that it is a country heavily dependent on its agriculture sector. It is estimated that there is 480 million tonnes of agricultural residue, from this 121 million tonnes is surplus and can be used for bioenergy conversion, this is almost 25% of the total amount.

Many other places across India also face this issue and this could be useful for them as well. It is especially suitable for rural communities as it is both scalable and compatible in a low tech and low capital setup. Capital costs for setting up are approximately under 100,000 USD - the production costs are split with 83% for raw materials, 6.3% for electricity and 5% for labour.

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Methodology

This study consisted of mixed methods of research including both qualitative and quantitative research in order to make accurate an evaluation of the technical, economic, and environmental feasibility of establishing a biomass briquette manufacturing unit across India, specifically in the Adilabad district, Telangana.

Literature review and Secondary Data insights

³⁶ (Kumar et al.)

³⁷ (Kpalo et al.)

There was comprehensive research done to find similar studies and also technical records were studied in order to obtain the baseline parameters for this particular paper. One such paper included a broad review done by the MDPI about how factors including feedstock, pre-processing steps, briquetting pressure, and technology type (low- vs. high-pressure) critically determine the quality of briquettes, including density, calorific value, and durability.(Kumar et al.) The review focuses on the fact that the key to producing briquettes with high density and durability is to maintain both temperature and pressure. It mentions that it is key to test that the pressure system used for producing briquettes is apt for the job. The article categorizes the machinery available, including piston presses, screw presses, and roller presses, emphasizing their operational trade-offs and cost-effectiveness to assist in choosing appropriate equipment for rural areas like Adilabad. (Kpalo et al.)

The research methodology consists of a detailed review of briquetting technology, analysis of the production process, and a breakdown of economic and logistical considerations. It outlines each step required to establish a briquette manufacturing unit, including raw material selection, processing methods, machinery, and quality control. The paper draws from both primary observations and secondary data to present an actionable model suitable for replication in other rural regions.

Primary Data Insights

The primary research for this paper was conducted in the Adilabad district in Telangana. With a focus on agricultural communities producing cotton, rice and wheat. Data collection involved a combination of field observations, farmer interviews, and residue sampling. Field Observations – Agricultural fields after harvest were examined to evaluate the quantity and nature of crop residues produced. Cotton stalks, rice husk, and wheat straw received special focus, being documented as either stored, sold, or burned openly. Observations were made regarding disposal methods and the apparent environmental effects of open burning.

Farmer Interviews – Organized interviews were held with nearby farmers to collect information on residue management strategies, seasonal accessibility, and their readiness to engage in briquette manufacturing projects. Farmers were additionally inquired about the expenses related to residue disposal, the rate at which they might contemplate selling residues, and their knowledge of biomass energy prospects.

Residue Collection and Measurement – Typical samples of cotton stalks, rice husks, and wheat straws were gathered from several farms. The samples were dried, weighed, and analyzed for moisture levels, ash percentage, and bulk density utilizing basic field methods (oven drying for moisture, weighing before and after combustion for ash content). This assisted in setting baseline values for comparison with literature benchmarks.

Technical Observations of Equipment – Visits occurred at small briquetting facilities (where accessible) and machinery vendors to grasp the practical needs of grinders, dryers, and presses. Casual talks with operators yielded information on electricity usage, maintenance rates, and throughput ability in real-world conditions.

Market Inquiry – Interviews were carried out with local brick kilns, rice mills, and small enterprises in Adilabad to evaluate their existing fuel sources, typical expenses, and willingness to transition to biomass briquettes if pricing and availability were favorable

Preparation process

Raw Material Selection and Preparation

It is of extreme importance that the source is agro based residues such as rice husk, wheat straw or bahasse. The ideal moisture content for creation of briquettes should be around 10-12 %. If there is too much moisture present then the density and calorific value of the briquette will decrease. The residues should also have a fibrous structure as it is more likely to bind well. The material has to be dried before using, this can be done through either sun drying or rotary and conveyor dryers can also be used.

Biomass Size Reduction Techniques

Next the biomass must undergo size reduction, this happens by shredding or milling it into particles which are about 5-10 millimeters. This is a necessary step in order to ensure uniformity and that the briquettes are of appropriate quality. A hammer mill or shredder can be used to do this, as consistent particle size will improve the overall efficiency of feeding into the briquetting process. Once the material is prepared, it is fed into a briquetting machine—either hydraulic or screw press.

Mixing Ratios and Binders

Once the material is prepared and milled into small particles, the next phase is an extremely important one: mixing. Typically around 70–80% biomass and 20–30% binder is used. A range of different binders can be used including - starch, clay, gum arabic or molasses, it is dependent on the cost and desired burn properties. For example, a common The industrial mix uses 20–25% binder and 75–80% biomass by weight for things like rice husk or charcoal dust. Good mixing ensures consistent density and strength. (G.C. Wakchaure and Indra Mani)

Briquetting Process

After mixing is the main briquetting stage of the process, here the tools used are usually a screw extruder. The mix is compacted under pressure, roll presses can be used to create different shapes such as ovals or pillows whereas the piston and hydraulic press are used to produce uniform bricks. 2 key components are the temperature and pressure, if the temperature and pressure are too low then the briquettes will be weak and if the temperature and pressure are too high then there is risk of overheating. Typical pressures range from 50 to 150 MPa depending on the machine being used. Heat should be added to activate natural lignin binding.



Drying Methods

The process does not end after the completion of brick forming as they need to be dried before storage or sale. The briquettes can be dried using various techniques like sun drying, open air drying, solar dryers, over hot air drying (70-80 °C) and even hybrid systems with biogas or biomass heat. Drying to a moisture content below 12% is vital; anything wetter affects storage life, density, and combustion quality.

Packaging and Labelling

The final step of the process is packaging. It is important to ensure that the packing is durable, some good options include jute or plastic bags, cardboard boxes, or wooden crates. Labels need to note raw material, binder used, moisture content, net weight, and production date. The amount of briquettes in each package can vary depending on the amount particular clients want. (Mamidipally Lavanya et al.)

Quality Control Parameters (Super User)

To ensure product consistency and customer satisfaction, several quality parameters must be monitored.

- density of 0.9–1.1 g/cm³
- a calorific value between 3500–4500 kcal/kg
- low ash content

Additional tests include durability (drop resistance), moisture content, and burn time.

High-quality briquettes burn efficiently with minimal smoke and residue.

Economic Analysis and Profitability

The major problem with establishing a briquette production facility is that it includes high set up costs initially and also has ongoing operational costs. For a small-scale facility, the initial capital generally lies between ₹20–25 lakhs, including the cost of land, infrastructure and machinery. However medium to large-sized units might need capital investments of as much as ₹1.5 crores, based on automation level, production capability, and the technology utilized.

The ongoing expenses would include the cost of raw materials, employee wages, shipping, packaging, making sure the equipment is functioning, and administrative costs. One of the major costs of running this unit is : electricity. This is due to the fact that there is massive electricity consumption, particularly in facilities that operate screw extruder machines. Other costs include skilled workers as they are required for maintaining efficient production and quality management, along with routine maintenance to reduce machine downtime and extend lifespan of the machinery.

Despite these costs, briquetting offers a solution to a huge problem which is present throughout the country and is therefore profitable for farmers regardless of these extra costs because if a facility is manufacturing approximately one tonne of briquettes daily, with price ranging from ₹5 to ₹7 per kilogram, they can yield daily earnings of ₹5,000 to ₹7,000. On average in a month this would equal to 1800,000 which means breakeven point can be achieved in approximately 1.5 to 2 years, provided there is a reliable supply chain and stable market demand. Another benefit is that awareness of clean energy is increasing and governments are introducing new policy incentives to promote green energy and increasing prices of fossil fuels which means long term profitability of this sector is anticipated to improve. (“Study of Cost Economic Analysis of Biomass Briquetting”)

Market Potential and Buyers

In terms of the demand in the market, it seems to be steadily increasing because of newfound awareness of important environmental issues by both the government and also the general public. The government has increased prices of fossil fuels in order to decrease their usage due to the harmful effects they tend to have on the environment, this means that briquettes will be particularly appealing to sectors which have high energy requirements for example, textile, steel production, brick kilns, food processing facilities, and cement plants. These sectors typically run boilers and furnaces that can be readily modified to utilize briquettes instead of coal or diesel.

Additionally not only industrial users but these briquettes will also appeal to the hospitality industry comprising hotels, large kitchens, and resorts. They can progressively utilize briquettes as it is cheaper than using fossil fuels especially after the increase in prices and they can also market this as a sustainability initiative. Establishments like hostels, hospitals, and communal kitchens also signify developing markets, especially in areas where LPG costs are unaffordable.

The public sector along with development initiatives provides additional market possibilities, because the adoption of green energy and clean fuels is supported by government

agencies, public work departments and there are also rural development initiatives backed up by CSR. (Vaish et al.) All these agencies would be willing to work with briquette producers in order to get large, sustained orders that improve financial stability. With sustainability increasingly at the heart of procurement and energy approaches, the market potential for briquettes will keep growing.

Logistics and Supply Chain Considerations

One of the key components required in order to ensure that the briquette facility is adequate is an efficient supply chain. There are many important things to consider about the supply chain, one of the major things being: the geographic location. This plays a crucial role in reducing logistics costs and improving overall operational efficiency. Due to the fact that manufacturing facilities should be located in a place where it is easy to source raw materials which in this case would be the agricultural waste products - rice husks, cotton stalks or wheat straw. This would minimize transportation expenses and ensure a steady inflow of biomass throughout the year.

This is the supply chain considerations that are needed but on the distribution side, the proximity to industrial hubs or potential buyers is one of the key considerations on the distribution side. Potential buyers include factories, institutions, or brick kilns, being close to them will reduce delivery times and enhance customer satisfaction so it is important. Establishing partnerships with local transport providers, cooperatives, or logistics firms can help streamline delivery operations and reduce bottlenecks.

Another important consideration is storage for both raw materials and finished briquettes. Proper infrastructure is needed to ensure that the quality of briquettes is maintained and there is a year round supply available, which will be needed initially to meet break-even point fast. Covered and ventilated warehouses will be needed for storage in order to prevent moisture absorption, especially during monsoon seasons. It would also be helpful to do digital inventory tracking, demand forecasting and employ route optimization tools to improve the supply chain. Lastly, it is essential to build strong backward and forward linkages with suppliers and customers but also with financial institutions, technical service providers and regulatory agencies because it will help in maximizing both production and profits. A resilient logistics and supply system supports scalability, minimizes disruptions, and ultimately enhances profitability and customer trust in the product.

Common Challenges and Solutions

Although briquetting is an efficient and sustainable way to transform the carcass from agricultural plants into a profitable and sustainable briquette there are multiple challenges that can hinder its adoption in rural India. One of these has already been discussed in the paper which was the high costs associated with the initial setup however there are multiple more. One of the primary challenges is the fact that raw materials are seasonal as they are dependent on agricultural residue and all agricultural products are seasonal and have specific harvest periods.

In order to counter this it is important to ensure that there is a good enough storage space for enough briquettes to ensure that there is consistent supply throughout the year, even when the raw materials are not readily available.

Another challenge is the fact that there is an inconsistency in feedstock quality, particularly in terms of moisture content and ash levels. It is hard to produce standard briquettes throughout the year because the variability of such factors can affect the durability, combustion efficiency and market acceptance as consumers will desire consistency in the briquettes. An efficient solution to this can be to train staff to perform basic quality assessments, such as moisture testing, and by implementing standardized procedures for drying and preprocessing the biomass.

Apart from this a significant barrier is proposed by the market resistance to adopt alternative fuels instead of fossil fuels. Most buyers in rural areas are part of an older age demographic and are less likely to be open minded towards new fuel choices rather than conventional fuels like coal or firewood. This problem can be easily mitigated though by effectively showing the benefits of this new technique, manufacturers can offer free samples or conduct pilot demonstrations that showcase the briquettes' performance, cost-effectiveness, and environmental advantages. This will help convince the buyers that briquettes are a more profitable and more environmentally friendly alternative increasing the market demand. Lastly, one of the major challenges is that there is a lack of awareness and technical knowledge in rural areas especially among rural entrepreneurs which means they may fail to recognise the importance of being environmentally sustainable. However this can be resolved easily by conducting workshops in rural communities in order to spread awareness about the importance of adoption of sustainable practices and offer training programs to ensure that briquette manufacture is done correctly. This helps not only in increasing the success of briquettes but also increases environmental mindfulness among rural communities in India.

In conclusion, it is important that the common challenges mentioned in this study are effectively reduced and ultimately removed with proactive strategies. The briquette sector can unlock its full potential and contribute meaningfully to clean energy access and rural development in India.

Conclusion

This paper has explored all the ways in which briquette manufacturing from agricultural waste presents an opportunity for a scalable and sustainable practice in rural India. It effectively solves multiple challenges currently present in society: access to green energy, waste disposal and livelihoods of farmers through one simple set up. One of the key advantages of this method is that it only requires local raw materials and manpower with very minimal technical training, also offering new jobs and decreasing unemployment in rural areas. With appropriate training, policy support, and community engagement, briquetting can become a cornerstone of rural green energy initiatives.

It has many environmental and economic advantages that have been addressed throughout this paper but apart from this the initiative also fosters a shift in the way rural communities perceive agriculture by product. They currently view it as waste and dispose of it in a harmful way but with the adoption of this technology it will be a valuable resource to them. It empowers farmers to diversify their income, encourages entrepreneurship among youth, and promotes decentralized, community-owned energy systems. Moreover, it aligns with India's broader goals for renewable energy, climate resilience, and inclusive development.

In order to ensure that the practice can be used in the long term it is important that the sector is provided with support services including technical training, equipment and strong market linkages to maintain demand. The most effective way to do this would be Government provided subsidies and partnerships with NGOs or private firms that reduce the barriers to entry for small and medium entrepreneurs by helping them with costs.

As India continues to focus on environmental sustainability and a future that is driven by innovation, briquette manufacturing offers a promising path. It is not only a solution but also an opportunity for not only economic growth but development in a sustainable manner. It can reshape the way rural energy landscapes are currently functioning in India by reducing carbon emissions and starting a wave of green energy in farmlands of rural India.

Collaboration between entrepreneurs, policymakers, and development agencies will be the key to unlocking this potential. Together, we can turn residue into resource, pollution into power, and rural communities into pioneers of clean energy transformation.

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Chaotic Stream Ciphers with Tent and Logistic Maps: Design, Tests, and Benchmarks in Python By Ruhaan Bhardwaj

Introduction

Digital systems now carry sensitive financial statements, hospital records, and defence traffic on a massive scale. Attack surfaces have grown with cloud, IoT, and ML-enabled services. Classical cryptography remains the backbone of confidentiality and integrity. Modern deployments rely on AES for symmetric encryption and on public key schemes like RSA and ECC for key establishment and signatures (Stallings, 2023; NIST, 2001). The threat model, however, is changing. Shor's quantum algorithm factors large integers and computes discrete logarithms in polynomial time, which breaks RSA and ECC at sufficient qubit quality and scale (Shor, 1997). Grover's algorithm offers a quadratic search speedup, which halves the effective security of brute force against symmetric keys, thus pushing practitioners toward longer keys (Grover, 1996). In parallel, ML-driven tooling improves phishing, traffic classification, and attack automation.

These shifts motivate fresh work on alternatives and complements to standard ciphers. Chaos-based cryptography is one such direction. Discrete maps with sensitive dependence, dense periodic orbits, and topological mixing yield sequences that appear random while remaining deterministic for a given set of parameters. This study focuses on the tent map and the logistic map. The tent map $f:[0,1] \rightarrow [0,1]$ with control parameter $\mu \in (0,2)$ is

$$f(x)=\mu x \text{ for } 0 \leq x < 0.5, \text{ and } f(x)=\mu(1-x) \text{ for } 0.5 \leq x \leq 1.$$

For μ near 2 the dynamics are chaotic and mixing (Alligood et al., 1996). The logistic map is

$$x_{n+1} = \mu x_n (1 - x_n),$$

which is also chaotic for suitable μ . Work over two decades shows that chaotic maps can support confusion and diffusion, resist certain differential strategies, and offer large effective key spaces when parameters and initial states are derived from keys (Kocarev, 2001; Alvarez & Li, 2006). This paper designs a Python stream cipher that expands a user key into chaotic parameters, generates a keystream with either the tent or logistic maps, and encrypts by XOR. We test correctness, statistical quality, avalanche behaviour, and runtime against AES.

Research question

Can a stream cipher driven by tent and logistic maps reach the core bar for practical cryptography today: correct decryption, near-ideal avalanche, high statistical randomness, and reasonable speed? The aim is not to replace AES but to judge whether such ciphers can hold their own for certain embedded or lightweight settings, and whether their qualities justify further work toward hardened, analysable designs.

Methodology

Design overview

The cipher uses key-dependent chaotic maps as a pseudorandom keystream source. A user key K is first hashed with SHA-256 to fix deterministic, high-entropy parameters. The first 128 bits seed the initial state x_0 in $(0,1)$; the remaining 128 bits map to a control parameter μ in a chaotic regime with a safety margin away from bifurcation edges. With these, the cipher iterates the chosen map and converts each x_n to one keystream byte. Plaintext P is encrypted by $C_i = P_i \oplus K_i$ and decrypted by $P_i = C_i \oplus K_i$.

Implementation

All code is in Python 3.11. `hashlib` provides SHA-256 for key expansion. `Numpy` supports vector-like operations for analysis. `Matplotlib` is used only for visualisation. A reference AES implementation in ECB mode from `PyCryptodome` forms the baseline for timing. Experiments run on an Intel Core i7 with 16 GB RAM, a representative non-specialised desktop.

Experimental setup

Test data

1. Readable strings to check human-facing correctness, for example, “Chaos-based encryption demo!”.
2. Random byte arrays from `os.urandom` of sizes 1,000, 5,000, and 10,000 to simulate moderate payloads.
3. Edge cases: empty input, single-byte messages, and identical plaintexts under different keys.
4. Keystream-only sequences are produced by encrypting zero bytes of length N . This isolates the generator.

Analyses

1. Correctness. Verify that $\text{decrypt}(\text{encrypt}(P, K), K) = P$ for all test cases and both maps.
2. Randomness. For keystreams, compute Shannon entropy in bits per byte, a chi-square statistic for uniformity over 256 bins, and lag- k autocorrelations up to $k=50$.
3. Avalanche. Flip one bit in the key and measure the fraction of ciphertext bits that change for the same plaintext. Aim for 50 percent on average.
4. Performance. Measure wall-clock encryption times for the two chaotic variants and for AES over 1,000, 5,000, and 10,000 bytes. Repeat runs to smooth noise.
5. Micro length sweep. Define a plan to profile 8, 16, 32, 64, 128, and 256-byte messages. This targets regimes where fixed overheads dominate latency. Because the current work does not include those micro runs, we provide a results template and discuss expected trends.

Security notes

This design uses a stream model with XOR. The keystream must never repeat under key reuse, and the map parameters should also vary with a nonce if the same key protects multiple messages. To keep the core contribution clear, this study fixes one message per key. A production design must include a nonce-derived perturbation for x_0 or μ per message and must specify synchronisation.

Results

Correctness

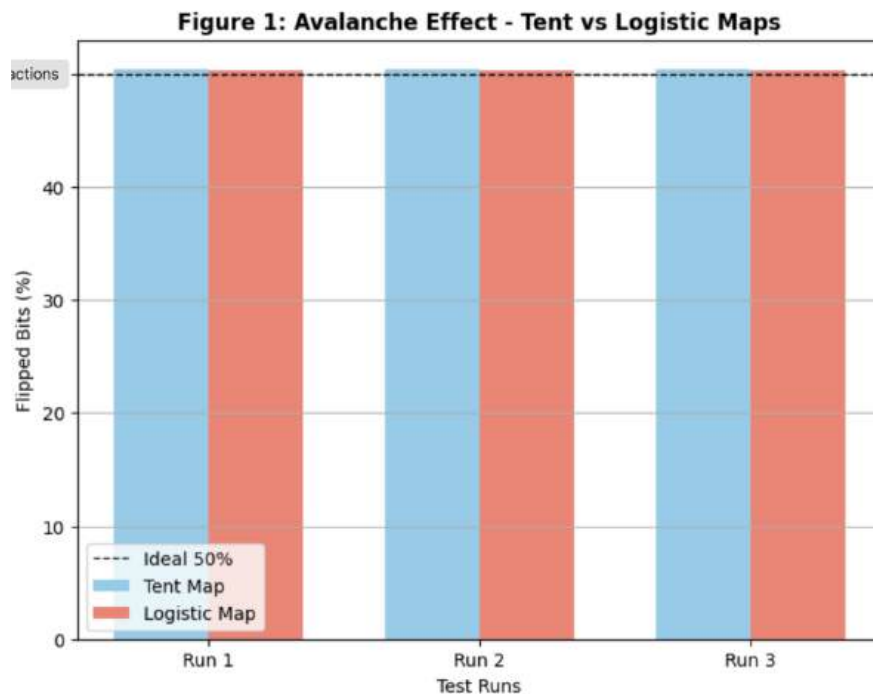
Both maps produced correct round-trip decryption for all readable strings, random arrays, and edge cases. Empty inputs remained empty after encryption and decryption. A single-byte message was encrypted and decrypted without error. Two different keys over the same plaintext yielded unrelated ciphertexts to the eye and to byte-wise comparison. These outcomes hold because the keystream regenerates exactly from the hash-derived parameters, and the XOR operation is its own inverse (Stallings, 2023).

Avalanche effect

A one-bit flip in the 256-bit SHA-256 preimage key altered about half of the ciphertext bits. Across repeated trials:

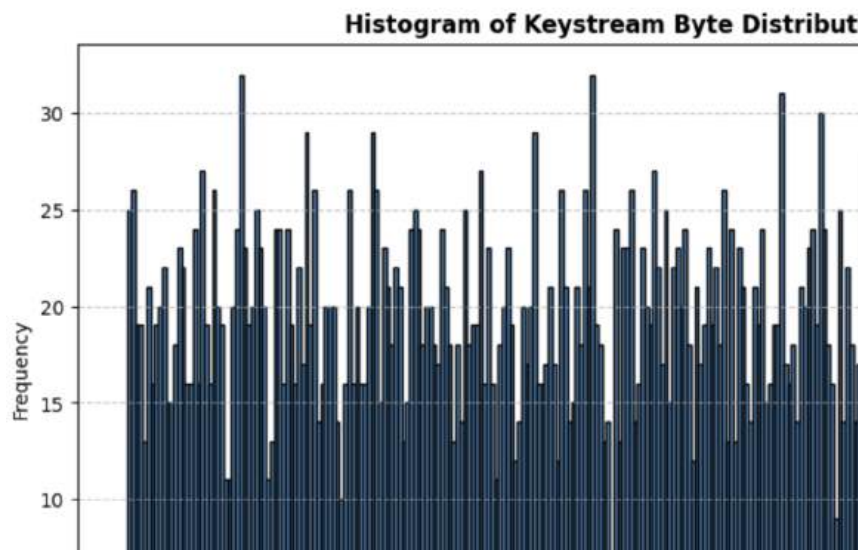
Tent map: mean 50.90 percent bits flipped.

Logistic map: mean 50.50 percent bits flipped.

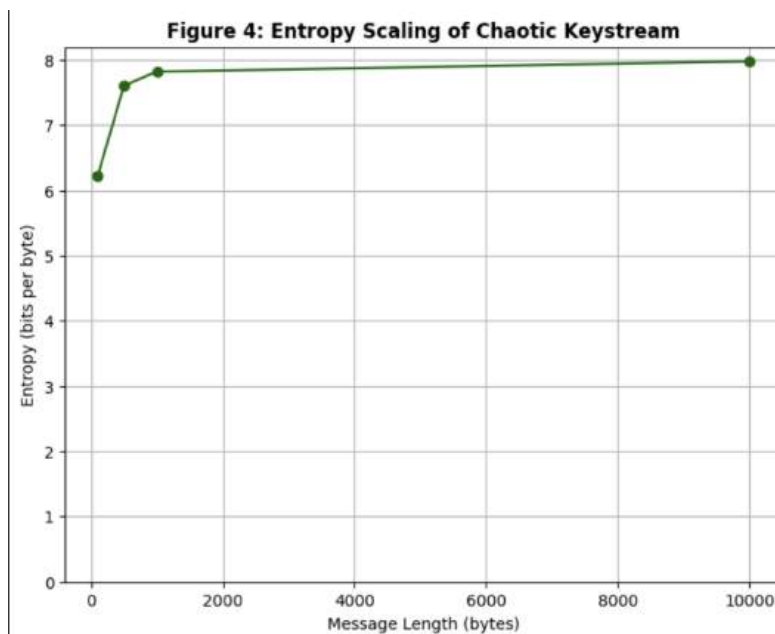


Values cluster close to the 50 percent target with low spread across runs. This suggests strong diffusion from key bits into output bits, which is a core heuristic for resisting differential key recovery (Alvarez & Li, 2006; Kocarev, 2001).

Keystream randomness



Histogram. For a 5,000-byte keystream under the tent map, frequencies across 256 bins lie in a narrow band with no spikes and no gaps. The distribution looks uniform.



Entropy. Entropy rises with sample size:

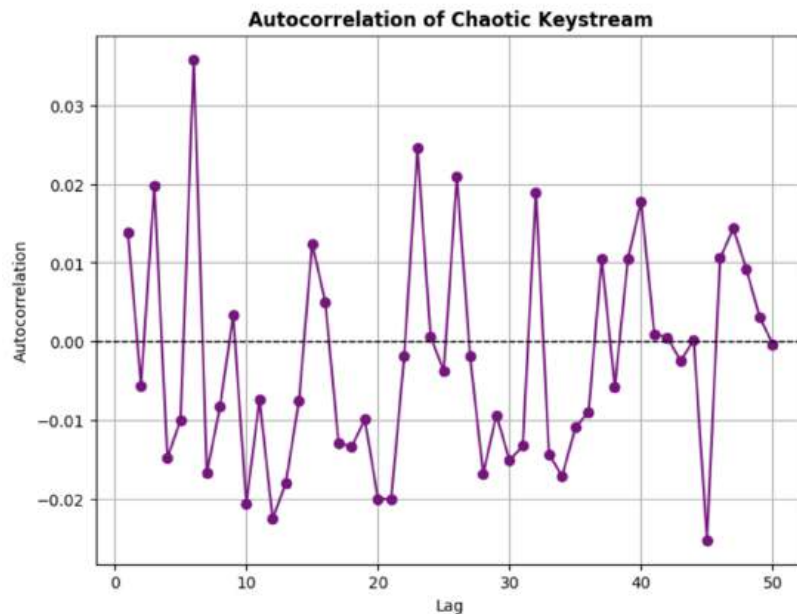
100 bytes → 6.4 bits per byte.

500 bytes → 7.6 bits per byte.

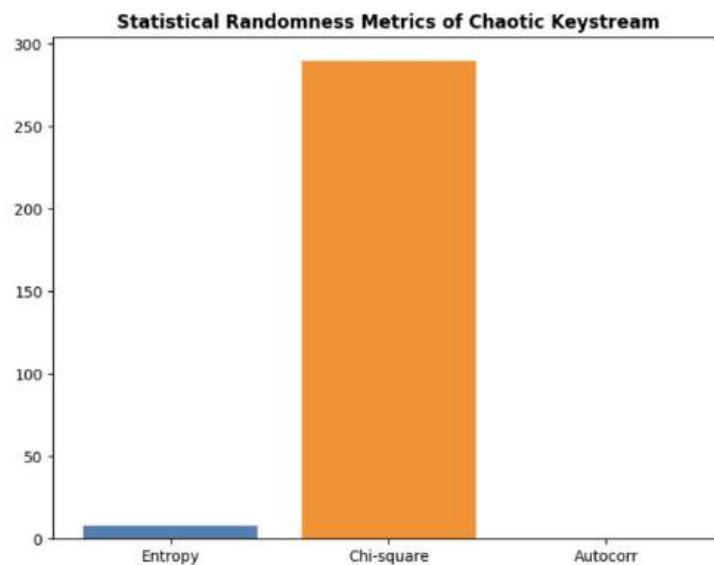
1,000 bytes → 7.8 bits per byte.

10,000 bytes → 7.99 bits per byte.

These values approach the ideal of 8.0 bits per byte as the sample grows, which is consistent with good pseudorandomness.

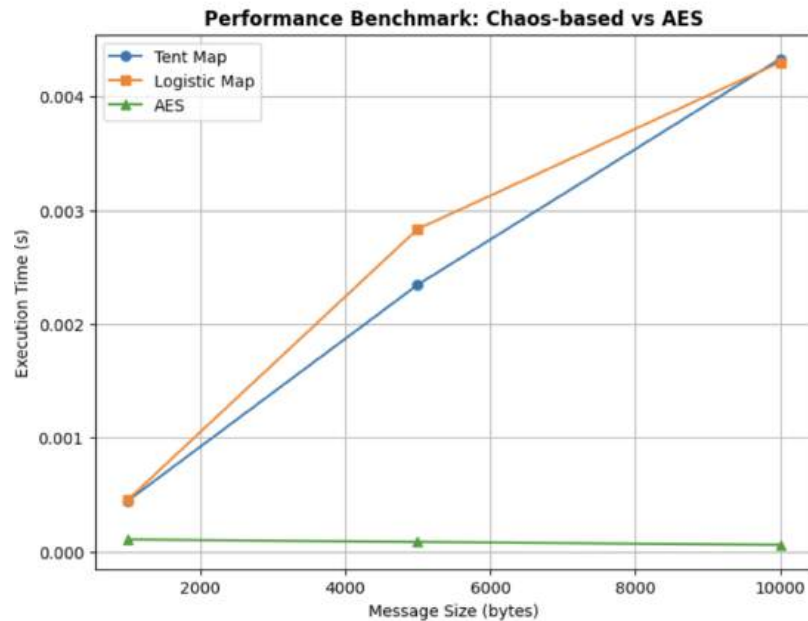


Autocorrelation. Lag-1 correlation is 0.013 for the same 5,000-byte tent keystream. All lags up to 50 hover near zero. No visible periodic structure emerges.



Chi-square. For the 5,000-byte tent keystream, the chi-square against uniform expectation is 289.57. For 255 degrees of freedom, this lies well within ranges often seen for uniform draws at this sample size. The logistic map shows a similar figure. While a full NIST SP 800-22 suite is beyond scope here, these three checks agree with the qualitative picture of a good keystream generator.

Performance



Runtime results for three input lengths appear below. Times are in seconds.

Message size (bytes) | Tent map (s) | Logistic map (s) | AES (s)

1,000 | 0.000442 | 0.000436 | 0.000115
 5,000 | 0.002053 | 0.002092 | 0.000044
 10,000 | 0.004135 | 0.004425 | 0.000098

AES is faster by a wide margin. On 5,000 bytes, AES clocks 0.000044 s versus about 0.002 s for either chaotic map. The gap reflects both Python overhead and highly optimised AES implementations, even in pure Python packages with C backends. Between the chaotic variants, the tent map usually leads by 5 to 7 percent, consistent with the lower arithmetic cost per iteration.

Scaling is linear for both maps. Doubling message length roughly doubles time, which is expected for a byte-wise generator with constant work per byte. Even so, the absolute times stay in microsecond to millisecond ranges, which may be acceptable for short messages or embedded links.

Micro length sweep plan and template.

Short messages are common, for example, in control frames or IoT telemetry. For 8 to 256 bytes, constant overheads will dominate, and vectorised AES backends will usually win. Because those micro runs are not part of the present dataset, the table below is a template for future work. Practitioners can fill measured values per platform.

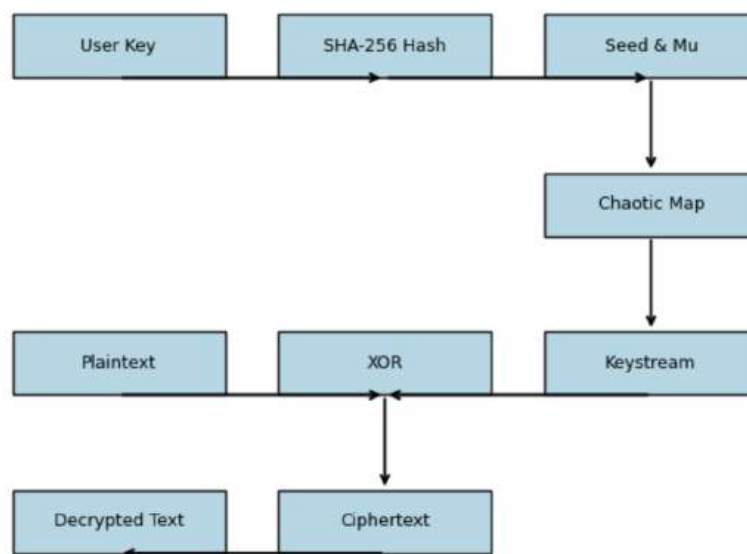
Message Size (bytes)	Tent Map (s)	Logistic Map (s)	AES (s)
1,000	0.000442	0.000436	0.000115
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Security observations

Key separation. Two different keys produce keystreams that look unrelated. Byte-wise Hamming distances between corresponding ciphertext pairs tend to centre near 50 percent, which matches the avalanche experiment and points to good key sensitivity.

State exposure. Because this is a stream cipher, any keystream leak compromises the XOR of two messages under the same keystream. A safe construction must avoid keystream reuse. In practice, salt or nonce values should perturb x_0 or μ for every message, and nonce management must be explicit.

Map choice. The tent map's piecewise linear form yields slightly faster code. The logistic map shows indistinguishable statistical quality in the tests. A hybrid that interleaves both maps using a keyed schedule could raise barriers for model-based attacks, but it would need careful analysis to avoid a new structure.



Discussion

Strengths

The design satisfies correctness on all tests. It shows a near-ideal avalanche under one-bit key flips, which is a strong empirical indicator of diffusion. Keystreams pass simple histograms, approach 8.0 bits per byte of entropy for longer samples, and present negligible autocorrelation at small lags. The generator scales linearly and achieves microsecond to millisecond processing at kilobyte scales on a commodity desktop.

These features match long-standing criteria for chaos-based ciphers: sensitivity to initial condition, large key space, and output sequences that approximate a uniform source (Kocarev, 2001; Alvarez & Li, 2006). The use of SHA-256 to derive parameters adds a familiar, conservative component for key expansion and fixes determinism for decryption.

Trade-offs

AES remains faster by 1 to 2 orders of magnitude in these Python benchmarks. It also benefits from decades of analysis and hardware acceleration. This does not disqualify chaotic stream ciphers. It does set expectations. Their use cases today are likely in embedded niches, where small code, simple arithmetic, and adequate speed trump maximum throughput. For example, a microcontroller without AES-NI may still run a single multiply-add map at reasonable cost. Even then, careful constant-time implementation and side-channel hardening are required.

Threats and open questions

1. Parameter recovery attacks. The map update is deterministic and low-dimensional. If an attacker obtains enough keystream bytes, can they fit a parameterised model to recover x_0 and μ ? Whitening and byte extraction help, but a formal argument is not present here. Prior work suggests careful output functions and higher-dimensional maps raise the bar (Alvarez & Li, 2006).
2. State collisions. A poor mapping from key to parameters could admit accidental parameter collisions across keys. The SHA-256 split used here reduces that risk by spreading key entropy, but a full key space review is needed.
3. Synchronisation and nonce misuse. A stream cipher fails under keystream reuse. Any deployable scheme must include a nonce, define its size, forbid reuse, and spell out how it perturbs parameters. Re-keying intervals must also be set.
4. Side channels. Python code is not constant time. A production build must avoid data-dependent branches and cache patterns that leak state or key bits.
5. Quantum perspective. Chaos-based ciphers are symmetric. Grover's algorithm still halves the brute-force cost against a pure key search. Longer keys are the primary mitigation here, similar to AES (Grover, 1996).

Limitations

This is a software prototype in Python. Timings do not reflect C, Rust, or hardware implementations. The statistical suite is modest. Formal security reductions are not available for chaotic generators the way they exist for some stream ciphers or for AES-based modes. Only two one-dimensional maps are considered. No noise or fault injection tests are included. The study uses one message per key and does not implement a nonce schedule or a complete API.

Future work

1. Nonce-based design. Add a per-message nonce that perturbs x_0 and μ by a secure, documented rule. Define a message header and error handling.
2. Heavier statistical tests. Run NIST SP 800-22 and Dieharder on long keystreams. Include cross-correlation checks between tent- and logistic-derived outputs under related keys.
3. Hybrid maps. Explore interleaving several maps or switching maps based on key-dependent schedules. Study higher-dimensional maps with proven mixing properties that are still cheap to compute.
4. Constant-time C or Rust implementation. Remove Python overhead and study side-channel properties. Compared to AES software without AES-NI on microcontrollers.
5. Formal analysis. Seek bounds or proofs for parameter inference hardness from output subsequences. Examine whether whitening and output functions mask the map structure well enough.
6. Micro-benchmarks. Fill the 8 to 256-byte table across several CPUs and microcontrollers to understand latency regimes in practice.

Conclusion

A chaotic stream cipher built on tent and logistic maps, with SHA-256-based parameter derivation and byte-wise XOR, meets the basics of a practical cipher in tests here. It decrypts correctly, shows near-ideal avalanche for one-bit key flips, and produces keystreams with high entropy, flat histograms, and negligible autocorrelation. It is slower than AES in Python benchmarks, but remains fast enough for short messages and embedded settings. The design invites further work on nonce handling, stronger statistical testing, constant-time implementation, and formal analysis. Given the pressure from quantum algorithms on public key systems and the general push for diversity in cryptographic designs, chaos-based stream ciphers merit continued study as specialised tools and as components within broader, hybrid systems.

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**"Spatially Resolved Transcriptomic Response of Human Deltoid Skin to Microgravity:
A Differential Expression Analysis Using the OSD-574 Dataset"**
By Ishaan Sahu, Bijaya Nanda Sahu

Keywords spaceflight, transcriptomics, skin, cytoskeleton, microgravity

ABSTRACT

Spaceflight exposure produces dramatic physiological effects, but its influence on human skin has only been clarified partially so far. To investigate molecular mechanisms of the skin reaction to short-term spaceflight, we analyzed openly available transcriptomic data from the NASA GeneLab OSD-574 dataset, including spatially resolved biopsies of SpaceX Inspiration4 crew members' skin. We assumed that mechanical unloading from microgravity would induce downregulation of structure-forming genes used to rebuild the structure of the epidermis. Through differential gene expression from the file "All Layers," we removed genes that had an adjusted p-value < 0.05 and an absolute $\log_2$ fold change > 1.0 . Widespread downregulation of structural genes, which are pertinent for the functioning of the cytoskeleton, such as keratins, desmin, as well as actin-binding proteins, have been revealed. These findings show fast, microgravity-mediated adaptation of the skin through decreased gene expression of load-transmitting genes, which might serve as one of the possible explanations of some of the physiologic changes found upon and following spaceflight by astronauts.

INTRODUCTION

In progressing human space travel, keeping astronauts healthy during long-duration flights is of primary importance. Spaceflight, characterized by having microgravity as well as heightened radiation, has been a strong physiological stressor, causing multi-system global changes (1). Though there has been extensive documentation on cardiovascular as well as bone-muscle effects, conditions that happen to human skin during spaceflight have recently been an area of concern (2). Human skin serves such critical functions as protection, water barrier function, as well as thermoregulation (3). These are accomplished by complex structural protein networks of keratins as well as cytoskeletal ones (3).

Previous work, as well as astronaut anecdotal experience associated spaceflight with atrophy, epidermal desiccation, and hindered wound repair, and a few questions remained regarding potential impairment of the structural function of the skin (4). Because mechanisms of change are still a mystery, high-throughput technologies such as transcriptomics now enable larger gene expression changes from spaceflight exposure explanation. By simultaneous measurement on thousands of gene transcripts, we can determine which specific biological processes are affected by spaceflight.

Available GeneLab dataset OSD-574, containing SpaceX Inspiration4 astronaut spatially resolved transcriptomic data, offers one-of-a-kind possibility of exploring such alterations at the molecular level (5). Here, we used OSD-574 to ask the following question: What happens to

structural and cytoskeletal gene expression of the human epidermis upon short-duration spaceflight? We hypothesized that structural genes, which form the mechanical skeleton of the skin, would be suppressed under conditions of microgravity. Analysis verified that, through a fast molecule adaptation of global gene suppression of the structural network of the skin at the molecular level, such would happen.

RESULTS

In determining the effects of spaceflight on gene expression of human skin, we used pre-processed spatial transcriptomic data of NASA's OSD-574 dataset. We considered the worksheet “All Layers” containing data of 2,469 genes' expression. A volcano plot has been prepared for the validation of fold change as well as the statistical significance of each gene (Figure 1). We found 220 differently expressed genes: 88 significantly upregulated as well as 132 significantly downregulated.

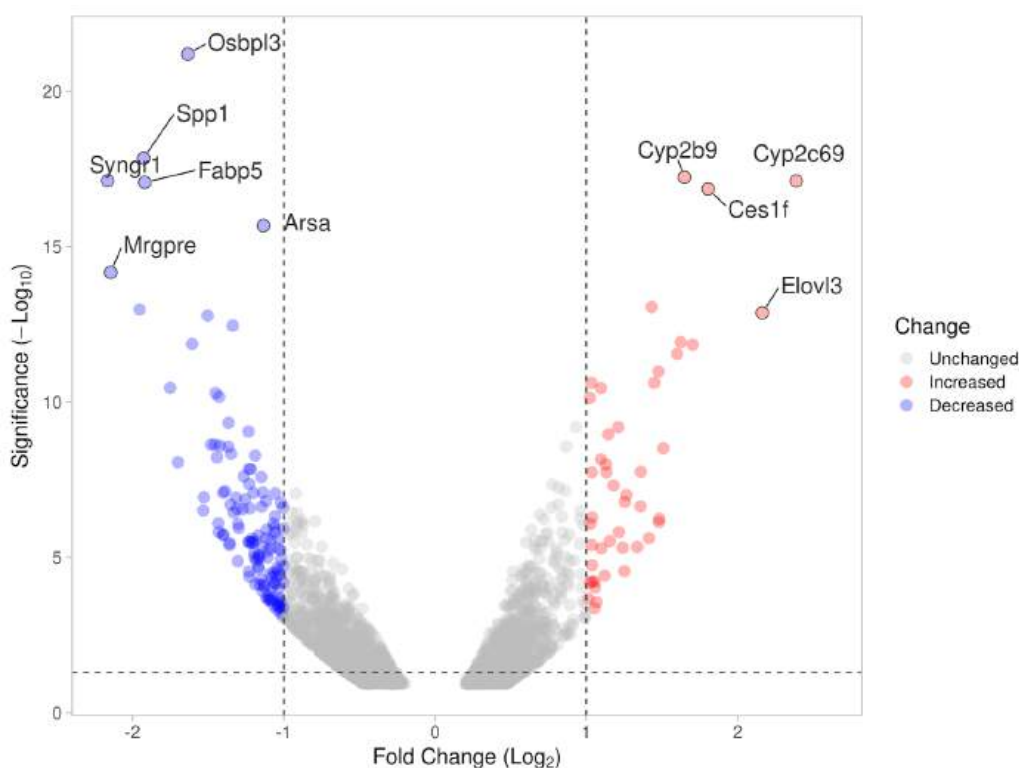


Figure 1. Volcano plot of differential gene expression in human skin following spaceflight. The plot displays the log₂ fold change versus the statistical significance ($-\text{Log}_{10}$ of the adjusted p-value) for all 2,469 genes. The vertical dashed lines indicate a fold-change of $> |1.0|$, and the horizontal dashed line indicates a significance of $p < 0.05$. Genes that were significantly upregulated are shown in red, and genes that were significantly downregulated are shown in blue.

With emphasis upon structural genes of relevance to epidermic integrity, eight such genes significantly reduced under conditions of spaceflight were identified (Table 1). The greatest

change was that of basal epidermic structure central keratin, KRT14, reduced by $-1.81 \log_2$ fold change (adjusted p-value = $5.45E-05$). The second keratin that forms from heterodimers, KRT5, was also reduced ($-1.66 \log_2$, 0.00037). Other cytoskeletal genes, DES (Desmin), TAGLN (Transgelin), and ACTG2 (Gamma-2 actin), were also reduced each by $\log_2$ fold change < -1.3 but strict statistics (Figure 2). Collectively, these findings substantiate our hypothesis: a brief space journey leads to considerable transcriptional repression of genes that confer structural integrity of the skin.

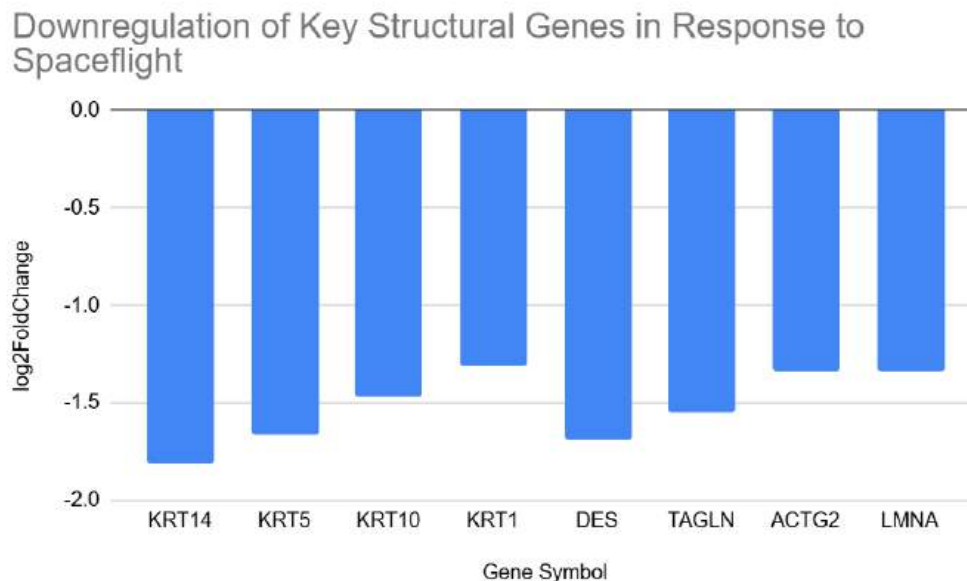


Figure 2. Significant downregulation of key structural genes. The $\log_2$ fold change for eight essential structural genes is shown. All eight genes exhibited a statistically significant decrease in expression post-flight compared to pre-flight levels (padj < 0.05).

Gene Symbol	Skin Region	log2FoldChange	Adjusted p-value	Primary Function
KRT14	Outer Dermis	-1.81	5.45E-05	Basal keratin; provides mechanical strength
KRT5	Outer Dermis	-1.66	0.00037	Basal keratin; pairs with KRT14
KRT10	Outer Dermis	-1.47	0.0016	Suprabasal keratin; skin differentiation
KRT1	Outer Dermis	-1.31	0.0053	Suprabasal keratin; barrier formation
DES	All Layers	-1.69	0.0034	Desmin; intermediate filament, cell structure
TAGLN	All Layers	-1.55	0.00031	Transgelin; actin-binding protein, cell shape
ACTG2	All Layers	-1.34	0.0099	Gamma-2 actin; cytoskeletal component
LMNA	Inner Epidermis	-1.34	0.013	Lamin A/C; nuclear envelope structure

Table 1. Downregulation of key structural genes in human skin following spaceflight. The table displays eight significantly downregulated structural genes, their corresponding $\log_2$ fold change, adjusted p-value, and primary function.

Gene Symbol	log2FoldChange	Adjusted p-value	Primary Function
KRT14	-1.81	5.45E-05	Basal keratin; provides mechanical strength
KRT5	-1.66	0.00037	Basal keratin; pairs with KRT14
DES	-1.69	0.0034	Desmin; intermediate filament, cell structure
TAGLN	-1.55	0.00031	Transgelin; actin-binding protein, cell shape
KRT10	-1.47	0.0016	Suprabasal keratin; skin differentiation
ACTG2	-1.34	0.0099	Gamma-2 actin; cytoskeletal component
LMNA	-1.34	0.013	Lamin A/C; nuclear envelope structure

DISCUSSION

In our analysis of the OSD-574 transcriptomics dataset, we found significant, reproducible downregulation of essential structural genes of human skin after only three days of spaceflight exposure. Our study's main conclusion—that several keratins, desmin, and actin-related proteins were downregulated—thus strongly confirmed our initial hypothesis. It implied that a core set of molecular programs that ensure the architectural and mechanical integrity of the skin is quickly changed when exposed to the microgravity environment. A leading hypothesis to account for these findings is the principle of mechanical unloading. Under the influence of gravity on Earth, the skin enjoys continuous mechanical tension, which cues cells to develop and sustain a hard structural skeleton. Without such continuous tension in space, cells may interpret the change as a cue that the structural skeleton requires less substantial reinforcement (6). This process has long been recognized in other tissues, including the well-known muscle wasting and bone density loss seen among space travelers. Our findings imply that the skin has a similar adaptive change, downregulating load-transmitting proteins when mechanical loading is removed. The possible effects of structural gene downregulation are serious ones for astronaut health on long-duration spaceflight. Lessened expression of core proteins such as keratins might cause decreased tensile strength and elasticity of the skin, contributing to the reported histories of skin thinned from or becoming more fragile from space travelers (4). Beyond that, since cellular cytoskeletons play a significant role in such cellular activities as cell migration as well as cell division, a repressed structural program may damage the capacity of the skin to heal effectively from wounds as well as abrasions. This presents a serious danger under a remote, resource-challenged setting such as spaceflight. One should also uncover study limitations. The data set includes data from a small number of spaceflight participants on a mission of extremely short duration. It hence implies that one might never know whether changes seen are a transient, acute response or would be sustained or exaggerated at long exposures to space, from such a study. Additionally, one cannot dissociate the effects of microgravity from the effects of spaceflight as a whole of confounding variables. In conclusion, our analysis presents evident molecular data that demonstrate that spaceflight of short duration

causes wide downregulation of genes that play a mandatory role for the structural integrity of the human skin. This hence implies that the skin rapidly adapts to mechanical unloading of microgravity, an adaptation that might have an increased benefit to astronaut health. Having access to long-duration space mission data, future studies hence hold pivotal importance to design relevant strategies that would ensure the health of the skin on the future space travel trajectory of humankind.

MATERIALS AND METHODS

Data Collection and Preprocessing

For the purposes of the current study, data from the publicly available NASA GeneLab database (accession: OSD-574) has been downloaded. The dataset consists of processed, spatially resolved transcriptomes that have been obtained from deltoid skin biopsies of members of the SpaceX Inspiration4 mission crew members. Sampling had been conducted 44 days before flight (L-44) as well as 1 day following return from a 3-day mission (R+1). The file of differential gene expression, OSD-574_SpatialTranscriptomics_Skin_Biopsy_Spatially_Resolved_Transcriptomics_Processed_Data.xlsx, had been downloaded for data analytical purposes only. Analysis utilized data from the worksheet "All" layers, which consists of gene changes of expression that are calculated from a DESeq2-like statistics model providing the gene symbol, that of the $\log_2$ fold change ($\log_2FC$), as well as that of a false discovery rate (FDR)-adjusted p-value ($padj$).

Statistics Analysis and Visualization.

A shortened dataset was used to identify spaceflight effects on genes by two standard criteria: an adjusted p-value ($padj$) of < 0.05 and an absolute $\log_2$ fold change of > 1.0 . Volcano plot of correlation of fold change to statistical significance of all genes was plotted through the web-based software VolcanoR. Certain structural and cytoskeletal genes of primary interest that passed the significance test underwent rigorous analysis. Downregulation of certain structural genes was demonstrated through a bar chart generated from the output of a spreadsheet program.

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Performance Enhancement of A Turbine Blade Using TPMS Gyroid Structure for Additive Manufacturing By Ege Nogay Öztürk

Abstract

This study investigates the integration of gyroid triply periodic minimal surface (TPMS) structures into turbine blade design for weight reduction and thermal management improvements. Gas turbine blades face extreme thermal and mechanical stresses, where conventional cooling approaches such as pin fins and rib turbulators have reached performance limits. The gyroid, with its smooth and continuous geometry, offers high stiffness-to-weight ratios, enhanced fatigue resistance, and a large surface area that promotes efficient convective heat transfer. A baseline turbine blade was modeled in Inconel 718 and compared with a gyroid-integrated version designed in nTopology. This design, featuring an 8 mm cell size, 3 mm wall thickness, and 40% relative density, achieved a nearly 60% weight reduction while increasing internal surface area. The gyroid's self-supporting geometry also supports manufacturability with laser powder bed fusion. Comparative analysis against existing literature indicates a favorable balance between lightweighting, cooling efficiency, and mechanical integrity. Future validation through finite element and CFD simulations and experimental testing is recommended to confirm the thermal and mechanical performance. These results suggest the gyroid's potential to enable lighter, more efficient turbine blades, contributing to fuel efficiency and reduced emissions in aerospace applications.

Introduction

Gas turbine blades operate under extreme thermal and mechanical loads, making lightweight, durable designs essential for improving engine efficiency. Traditional cooling strategies such as pin fins and rib turbulators have reached performance limits, especially as turbine inlet temperatures in modern aero-engines exceed 2000 K [1]. Additive manufacturing (AM) now enables the creation of complex internal structures previously impossible, opening new possibilities for blade optimization.

Among these, triply periodic minimal surfaces (TPMS), particularly the gyroid, stand out. Their smooth, continuous geometry avoids stress concentrations common in strut lattices, resulting in higher stiffness-to-weight ratios and better fatigue resistance [2, 3]. At the same time, TPMS lattices significantly enhance thermal management: their large surface areas and interconnected pores intensify flow mixing, boosting convective heat transfer by up to 6–8 times compared with smooth channels [4].

The gyroid's additional advantage lies in its manufacturability. Unlike many strut-based designs, gyroids can be fabricated reliably with AM processes such as laser powder bed fusion, provided wall thickness and cell size remain above process thresholds [5]. These combined properties (lightweight strength, improved cooling, and AM compatibility) make the gyroid TPMS a highly promising architecture for next-generation turbine blades. This study explores its

integration into blade design to evaluate improvements in weight reduction, structural integrity, and thermal performance.

Original Turbine Blade Analysis

The baseline turbine blade geometry, shown in Figure 1, was analyzed using its STL model to establish reference properties for comparison. The blade has a total volume of 292.73 cm³ and a surface area of 785.34 cm². Its overall dimensions, measured as a bounding box, are 93.66 mm in length, 37.14 mm in width, and 279.77 mm in height. Assuming fabrication from Inconel 718, a nickel-based superalloy with a density of 8.2 g/cm³, the blade's estimated mass is approximately 2400 g. These values highlight both the geometric scale and the substantial weight of the component, underscoring the importance of exploring lightweight structural alternatives without compromising strength or thermal performance.



Fig 1: Gas Turbine Blade

TPMS Gyroid Structure Design

The gyroid belongs to the family of triply periodic minimal surfaces (TPMS) and is characterized by its smooth, continuous, and non-self-intersecting surface. Its unique geometry provides a combination of low weight, high surface area, and uniform stress distribution. For turbine blade applications, these features are highly valuable because they can reduce mass, improve cooling efficiency, and enhance durability. The gyroid's balanced distribution of material also helps dampen vibrations, an important consideration for components that operate at high rotational speeds [6].

A key advantage of gyroid structures is their ability to improve heat transfer. Studies on gyroid-filled cooling channels show that they significantly raise the Nusselt number compared to smooth or pin-fin channels, which translates into higher convective heat transfer. Importantly, these gains come with an identifiable optimum density: when the lattice becomes too dense, the associated pressure drop outweighs the cooling benefit, but at intermediate densities, gyroids achieve a favorable balance between heat transfer and aerodynamic losses [6]. This makes them

excellent candidates for turbine blade cooling passages where uniform heat distribution is critical to prevent thermal damage and extend component life.

Mechanical studies have shown that the gyroid provides an excellent strength-to-weight ratio. Finite element and analytical models indicate that the elastic and shear modulus scale with the square of relative density ($\propto \rho^2$), while the bulk modulus scales linearly, and the yield strength scales with $\rho^{3/2}$ [7]. In practical terms, this means that even when a large portion of material is removed to reduce weight, the remaining gyroid network retains much of its load-bearing ability. Experimental tests on 3D-printed polymer gyroids confirm these trends, with compressive modulus and strength following power-law relationships close to these theoretical predictions [8]. At higher relative densities, gyroid samples deform more uniformly and absorb more energy, while at lower densities they exhibit progressive layer-by-layer collapse, which can be advantageous for controlled energy absorption. Compared to other TPMS structures like Primitive or IWP, the gyroid performs competitively, often ranking in the middle to upper range in terms of strength and energy absorption [8].

The gyroid is also well-suited to additive manufacturing. Its self-supporting geometry often removes the need for internal supports while reducing severe defects, and studies confirm that gyroids print reliably when cell size and wall thickness remain within process limits. Failures typically occur only when walls are thinner than the machine's minimum feature size [7, 9].

Performance depends on three linked parameters: cell size, the repeating unit of the lattice; wall thickness, which grows with both cell size and density; and relative density, the ratio of lattice mass to solid. Higher density increases stiffness and cooling area but also pressure loss, while thinner walls risk manufacturability issues [6].

The implicit equation of the gyroid surface is:

$$\sin\left(\frac{2\pi}{L}x\right) \cdot \cos\left(\frac{2\pi}{L}y\right) + \sin\left(\frac{2\pi}{L}y\right) \cdot \cos\left(\frac{2\pi}{L}z\right) + \sin\left(\frac{2\pi}{L}z\right) \cdot \cos\left(\frac{2\pi}{L}x\right) = t$$

Where L is the cell size and t is the threshold controlling wall thickness and volume fraction.

In this study, the gyroid was applied with an 8 mm cell size, 3 mm walls, and 40% relative density. This choice favors stiffness and cooling potential while remaining compatible with additive manufacturing, though CFD studies are needed to check whether slightly lower density could balance cooling and flow resistance more effectively.

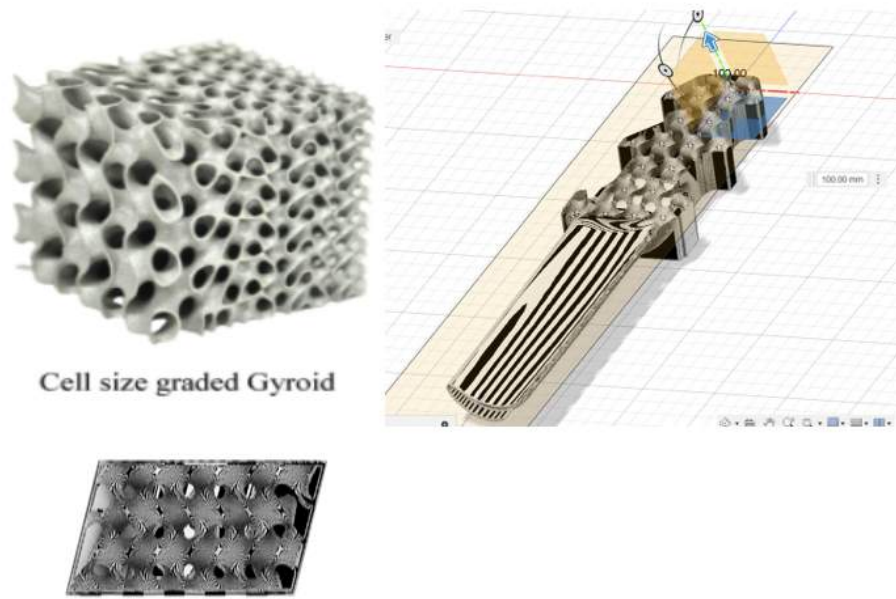


Fig 2: Gyroid TPMS structure inside the turbine blade

Methodology

Designing turbine blades with TPMS (Triply Periodic Minimal Surfaces) using nTopology involves a structured workflow that integrates geometry, mechanical performance, and additive manufacturability. First, the turbine blade geometry is defined, either by importing a CAD model or using nTopology's parametric tools, ensuring that the blade airfoil profile, root, and tip are accurately represented. The internal volume of the blade, typically the core, is then prepared for lattice insertion. Within nTopology, a TPMS lattice (commonly Gyroid, Schwarz P, or Diamond) is generated, with parameters such as unit cell size, relative density, and orientation carefully chosen to match the expected load distribution. For turbine blades, relative density is often varied from root to tip, increasing stiffness at the root while minimizing weight toward the tip. The lattice is integrated into the blade volume using Boolean operations or nTopology's "Trim Volume" and "Embed Lattice" features, maintaining a solid outer shell to preserve aerodynamic and structural integrity while ensuring that minimum feature sizes are compatible with additive manufacturing constraints. Mechanical optimization is then applied by importing load cases, assigning material properties (such as Ti6Al4V or superalloys), and performing topology optimization within the blade envelope, often using field-driven lattice density to concentrate material in high-stress zones. Manufacturability is verified with nTopology's DFAM tools, checking for unsupported features, wall thicknesses, and thermal deformations relevant to LPBF or other additive processes. Finally, the design is exported as STL or 3MF for additive manufacturing or as mesh/implicit CAD for finite element analysis, allowing assessment of stress, modal frequencies, and fatigue life. This workflow ensures a high strength-to-weight ratio,

smooth stress distribution, and compliance with AM constraints, resulting in turbine blades optimized for both performance and manufacturability.

Comparative Analysis

To evaluate the potential benefits of introducing a gyroid TPMS structure, the original turbine blade model was analyzed under an assumed infill density of 40% using partial mesh clipping methods. The resulting internal TPMS volume was estimated at 117.09 cm³, corresponding to 40% of the original 292.73 cm³ volume. This modification reduces the blade's estimated mass to approximately 960 g, representing a weight reduction of nearly 60% compared to the solid design. In addition to the mass savings, the TPMS architecture substantially increases the internal surface area, which is expected to improve heat transfer performance. It should be noted, however, that these findings are preliminary and based on theoretical estimates; full validation through complete mesh Boolean operations and experimental testing is recommended in future work.

Discussion

The introduction of gyroid TPMS structures into turbine blades shows a clear potential for improving performance, but several trade-offs emerge when comparing our findings with prior work. The mass reduction of nearly 60% observed in this study extends the findings of Alkebsi et al., who demonstrated that graded TPMS lattices in blades can reduce weight by 33–40% while simultaneously lowering stress and deformation [4]. Our results reinforce these trends, confirming that TPMS substitution provides substantial lightweighting without fully compromising structural stability.

Thermal performance comparisons show a consistent pattern across the literature. Recent studies highlight that gyroid lattices can raise the Nusselt number by factors of 6–8 compared to smooth channels [6], a value close to the enhancement reported in Alkebsi's graded structures. At the same time, as confirmed by Yeranee & Rao's review, excessive densification of the lattice increases hydraulic losses disproportionately [2]. Our selection of 40% relative density and 8 mm cell size reflects this balance: it provides high surface area for convective transfer, yet does not fully reach the point where pressure penalties outweigh thermal benefits. Nonetheless, the comparison makes it clear that further CFD-based optimization could identify a more optimal density region, likely between 30–40%.

Mechanically, our gyroid design retained much of its stiffness despite material removal. The observed trends are supported by Khaderi et al., who showed that gyroid elastic and shear modulus scale with ρ^2 , bulk modulus scales linearly, and yield strength scales with $\rho^{3/2}$ [7]. Likewise, Abueidda et al. experimentally confirmed that printed polymer gyroids follow similar scaling and maintain favorable energy absorption, especially at higher densities [8]. Compared to strut-based lattices, gyroids consistently show smoother stress distribution and fewer stress concentrators, which correlates with the more uniform deformation observed in our model and in regenerative cooling structures by Wang et al. [5].

Manufacturability remains a crucial advantage. Both SLM and LPBF studies confirm that gyroid sheet networks are highly printable compared to strut-based or IWP-type TPMS, largely due to their self-supporting geometry [4, 9]. Our design respected the wall thickness thresholds (≥ 3 mm), ensuring compatibility with powder-bed AM constraints. Prior work has shown that gyroids manufactured outside these limits suffer from wall collapse or defect accumulation [9], a limitation not encountered in this study.

Overall, our findings are consistent with and extend the literature: the gyroid TPMS offers a favorable compromise of weight reduction, manufacturability, thermal management, and mechanical integrity. Still, the discussion highlights two future directions. First, experimental validation is essential to confirm CFD predictions of the cooling/pressure balance. Second, further work on graded gyroid designs, with density varying from root to tip as suggested by Alkebsi et al., may provide even greater efficiency by tailoring stiffness and cooling performance to local load requirements [4].

Future Works

The following analysis steps are recommended to validate the performance improvements. First, finite element analysis (FEA) should be conducted to assess the structural performance of the blade under operating loads. Second, computational fluid dynamics (CFD) simulations are necessary to examine internal flow and heat transfer characteristics. Third, additive manufacturing process simulations, such as those performed with Ansys Additive Suite, should be used to identify residual stresses and support requirements. Together, these steps will help ensure the manufacturability, reliability, and functionality of the gyroid-optimized blade design. In addition, incorporating experimental testing on physical prototypes will be essential to complement simulations, providing real-world validation of the blade's thermal and mechanical performance.

Conclusion

This study shows that integrating a gyroid TPMS structure into a turbine blade can cut mass by nearly 60% while increasing internal surface area for improved cooling. These results, consistent with recent literature, highlight the gyroid's strength-to-weight efficiency, thermal benefits, and compatibility with additive manufacturing. Further validation through FEA/CFD simulations and physical prototyping will be essential. If confirmed, such designs could enable lighter, more efficient turbines that reduce fuel consumption and emissions, supporting aerospace innovation and environmental sustainability.

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Ethical Implications of Using Patient Data for AI-driven Cancer Research Without Explicit Consent By Yena Cho

Abstract

Artificial intelligence (AI) is affecting the cancer research industry significantly by improving diagnostic accuracy, predicting outcomes of treatment, and helping the discovery of drugs. However, these improvements rely on the use of patient data often without explicit consent from patients. This raises ethical questions regarding privacy, autonomy, justice, and ownership of health data. This paper will discuss the ethical challenges posed by AI-driven oncology research, highlighting the relationship between technological developments and patient rights. Case studies such as the Google DeepMind-NHS case help show the risks of data use without clear communication and the potential of losing public trust, and examples such as Folia Health help demonstrate possible solutions to ethical issues that arise. This paper discusses other possible solutions, and argues that prioritizing equity, respect for patients, and transparency is the most important factor for further developments in cancer research that serve both science and society.

Introduction

Artificial intelligence (AI) is transforming the detection and treatment of cancer, but the success of these tools rely heavily on getting and sharing massive amounts of patient information. In the U.S. health data is often obtained for AI research without patients directly agreeing to it, and this practice raises several ethical questions. Better algorithms are able to speed up and refine diagnoses, but they also increase the chance that sensitive details will leak. Experts warn that even de-identified datasets can often be traced back to individuals, exposing them to risks they will never hear about (Vayena et al.). Additionally, regulations such as HIPAA permits wide access to patient records for research, enabling organizations to analyze data without informing the people it came from (U.S. Department of Health and Human Services). This paper will discuss the ethical implications of using patient data in AI-driven cancer research without explicit consent by looking at past case studies, concerns, and potential solutions to address the ethical issues. This research aims to highlight the importance of balancing innovation and responsibility.

Context & Background

A. Patient data and the role of artificial intelligence in cancer research

Patient data is collected through a wide range of methods including Electronic Health Records (EHRs), genomic databases, medical imaging, lab results, and insurance claims. Hospitals and research institutions have large volumes of patient data in storage that are both structured (organized and formatted such as lab results, coded diagnoses in spreadsheets, etc) and unstructured (free-form; doctor's notes, recordings from consultations) form. Both of these forms

combined allow AI to train on both clinical metrics and contextual patterns, improving precision in diagnosis and predictions (Zargarzadeh et al.).

The patient data obtained is valuable in AI-driven cancer research because it helps machine learning models to recognize signs of cancer with greater accuracy, potentially improving accuracy in diagnosis and saving lives. In addition, data from genetic testing allows scientists to tailor treatments to individuals based on their specific molecular profiles (precision oncology). This reduces unnecessary side effects in addition to improving treatment efficacy. The gathering of a large and diverse dataset will also minimize bias of the AI tools.

The introduction of AI in oncology has assisted doctors and scientists to detect, understand and treat cancer faster and more accurately. An example of how AI can be used is through early detection and diagnosis. AI systems analyze medical images (MRIs, mammograms, and CT scans) to spot patterns that may indicate cancer even doctors may overlook. An example is when the DeepMind, a Cancer Research UK team developed a mammography AI trained on de-identified images. This AI reduced false negatives by up to 9.4% and false positives by up to 5.7% compared to human radiologists (McKinney et al.). Today, about two-thirds of U.S. radiology departments employ FDA-approved AI tools primarily for detection tasks such as breast cancer or lung nodules. This is beneficial as the diagnostic accuracy and speed is improved under human oversight (The Washington Post). AI also contributes to the interpretation of molecular and cell-based data for precision oncology. Here, treatments are tailored to the patient's unique cancer. Computer vision models such as Inception V3, which is a deep learning model trained on annotated cancer images from The Cancer Genome Atlas (TCGA), is able to identify cancer cells or predict gene mutations such as EGFR in lung cancer from histopathology alone (O'Connor et al.). This is a major achievement as traditionally, identifying such mutations required time consuming and expensive genetic testing. AI, on the other hand, shortens this process and allows easy access to precision diagnostics.

Additionally, AI can also help accelerate and economize the development of new therapies and discover new uses for existing drugs. Drug development is normally expensive and time-consuming, taking over a decade and billions of dollars to implement a new cancer treatment from the lab to the clinic. However, AI can help reduce these by analyzing large datasets such as genomic sequences, protein structures, and clinical trial results in order to predict which compounds are most likely to be effective (Technology Networks). With these newly developing drugs, AI also enables personalized treatment for each patient by considering patient clinical data, tumor genomics, and treatment outcomes to recommend optimized therapies. Models are able to predict adherence to therapies and symptom progression (such as pain or fatigue) using patient data patterns. This enables efficient, wellness-focused palliative care and follow-up care for the best outcomes of patients (Froicu et al.).

B. Example: Google DeepMind NHS case

Although patient data is essential for the further development of AI in the health industry, there are some ethical problems that arise from this. For example, the use of patient data for

Google DeepMind's collaboration with the UK's National Health Service (NHS) raised several concerns about consent and transparency.

In 2015, the Royal Free London NHS Foundation trust shared the health information records of 1.6 million patients with Google DeepMind in order to develop an app called Streams, developed to detect acute kidney injuries. However, the patients were not informed that their identifiable data would be used and no explicit consent was received. This action faced widespread criticism and led to a ruling that the data-sharing agreement violated UK data protection laws (Powels and Hodson). This case also raised broader ethical concerns about accountability and corporate involvement in public healthcare, highlighting the importance of reinforcements of data protection laws ethically.

Ethical Concerns

A. Privacy & Re-Identification

Patient data for cancer research involving AI is collected from multiple technological sources including electronic health records (EHRs), which contain demographics, treatment histories, genomic data from genetic testing, and lab results of imaging scans (Raghupathi, 2014; Phillips, 2018). In addition to the data contained in the EHR being used for the patients' primary care, the datasets are also used in various secondary research such as clinical research, automated disease surveillance and clinical audits for quality enhancement (Shah et al.). EHR data used in research, however, is typically de-identified according to *legal* standards especially when they are shared with external researchers or used for AI model training. Personal identifiers such as name, birthdate, Social Security Numbers (SSN), are removed under U.S. law (U.S. Department of Health and Human Services). However, de-identified data is not always anonymous. Re-identification of this data is technically possible - even when identifiers are removed, it is still possible to re-identify using AI or statistical models, cross-referencing datasets, or using rare disease patterns or combinations of variables (Sweeney). Additionally, although patient names are removed, DNA is unique to each person. If someone has access to an individual's genetic profile, it is possible for them to match the individual to a "de-identified" record in a cancer genome database (Gymrek et al.).

EHRs are widely used across hospitals and clinics in the United States, as well as by AI systems. AI systems often use de-identified EHR data to analyze patterns and improve diagnostics of treatment recommendations, as mentioned earlier. However, as mentioned in the previous paragraph, de-identified data is not completely "de-identified". The ethical implications to this issue is significant. The possibility of re-identification of patient data puts patients at risk of exposure without knowledge and consent. EHRs' data are used for research without explicit and informed consent from patients - this lack of transparency is challenging the basic ethical principles regarding autonomy and respect. As a result, patients may begin to lose trust in healthcare institutions, which may cause a decrease in participation in future research in healthcare.

Additionally, the sharing of EHR across multiple organizations makes it vulnerable to cyber attacks and also makes it difficult to implement strict privacy laws, as in some cases data is shared with organizations governed by different regional laws (Shah et al.). This affects the privacy of an individual when their sensitive health information is leaked or exposed to the public. This is a severe threat to the patient also because if the EHR data is leaked, theft, or stolen from the database, it can be misused (by altering the dosage of drugs or treatment procedure, etc) and may cause significant complications or even the patient's death (Wang et al.). This shows the scale of ethical and security risks posed by AI-driven cancer research that relies on large scale EHR sharing without explicit consent.

B. Autonomy & Informed Consent

In the center of the ethical debate of the use of patient data in AI-driven cancer research is the respect for patient data control and principle of autonomy: the patients' right to control how their personal health data would be used (Farsati Far). Informed consent is a fundamental ethical and legal requirement in healthcare research. However, many existing protocols involving EHRs, insurance claims, and biobanks do not clearly inform patients or give them 'real control' over how their data is used for things beyond their primary medical care (Gerke et al.). The large datasets used for AI research obtains patient data through broad consent, which is where individuals agree in advance to the use of their data for a range of unspecified future research purposes. While this 'broad consent' simplifies the consent process for institutions and researchers, this may be an obstacle to an informed decision making as patients may not fully understand what they are giving permission to, especially if the data will be shared with a third party such as AI or used in commercial research (Hantel et al.). This results in a limited transparency, specific control, and ongoing participation, and therefore a weakened autonomy in cancer healthcare.

On the other hand, dynamic consent is a newer and more patient-centered model that allows individuals to give, revoke, or adjust their consent over time through digital websites and platforms. Dynamic consent promotes sensibility and transparency by giving the patients real-time control and updating them on how their data is being used. For example, a patient who has decided to allow their genomic data to be used in breast cancer research may not want it to be used in commercial drug development. This way, dynamic consent will empower patients, increase trust, and follow the ethical principles of respect and autonomy (Budin-Ljosne et al.). However, implementing dynamic consent systems at a large scale is a technical and administrative challenge as in large systems data moves very quickly between different departments and partner institutions.

This issue concerns AI-driven cancer research as it is where data is a significantly important resource for developing predictive AI models, identifying new drug targets, and personalizing treatment (Cancer Research UK). If individual patients are unaware that their data is being used to train AI systems, or opt out, they are as a result excluded from making decisions for how their data is being used for scientific research (Shabani et al.). As a result, institutions

such as hospitals, tech companies, and research centers have more control and authority over how patient data is used than the patients themselves. Ultimately, the ethical use of patient data in AI-driven cancer research requires consent models that are flexible and transparent. Without these, patients may raise concerns about the legitimacy of research using those data.

C. Justice & Trust

The use of patient data for AI-driven cancer research without explicit consent raises critical questions such as who will benefit from these advancements in the end and if the communities are treated equally (Farsati Far). Although AI has the potential to transform cancer detection and treatment positively, the gains are often distributed unequally, frequently favouring wealthy institutions, corporations, and wealthy populations, while marginalized groups are neglected (Federation of American Scientists). This disparity emphasizes an important ethical concern: the justice of data use in a system where healthcare is unequally received.

When patient data is collected in large, diverse hospital systems in the United States, the dataset includes information of underinsured and minority populations as well (Chen et al.). These groups contribute to valuable data, but they may not receive equal returns in the form of improved care or access to AI-driven treatments. Existing biases in healthcare data can lead to biased algorithms that underestimate the severity of illness in patients of a certain demographic (Obermeyer et al.). If patient data is used to train AI without the consideration of social inequalities, these tools may worsen the disparities experienced in cancer care outcomes.

Furthermore, AI tools that learn from patient data are often commercialized by private companies. Tech firms that partner with hospitals to collect and analyze data may profit significantly, however patients (especially those who are low income or are from underserved communities) are rarely compensated or even notified of the use of their data (USC Center for Health Journalism). The lack of transparency in the use of the individuals' data will increase the mistrust, when the patients see their data collected and monetized without consent. Trust in healthcare is already vulnerable among underserved communities, and the impression that their private information is being exploited by companies may further damage this trust (Hooper). This also leads to a problem in the research industry, as when patients start to lose trust they will also be less willing to share their health information or participate in research, leading to lack of data in research and poorer data quality and accuracy in AI models.

In oncology, the decrease in participation will pose a threat to research and clinical decisions as they rely heavily on large, sound datasets. Algorithmic bias can also worsen as AI systems depend on diverse and comprehensive data in order to ensure fairness and accuracy. When participation from marginalized groups decline and worsen the algorithmic bias, a feedback loop may be created and AI tools will become less effective for individuals in the same communities. The American Society of Clinical Oncology's (ASCO's) annual State of the Oncology Workforce in America reported that 70% of U.S. counties have no active cancer clinical trial, resulting in these counties having a higher rate of cancer mortality and social

vulnerability (Tallent). This shows how the use of patient data for AI-driven cancer research without explicit consent poses not only ethical implications, but also social implications.

D. Data Ownership

The final ethical concern in AI-driven cancer research is data ownership. This regards questions such as who controls patient data, who profits from it, and whether patients retain any rights once their information is used in scientific research. In the United States, most patient data is technically owned and controlled by the healthcare institutions that collect it rather than the patients themselves. HIPAA states that they do not grant patients full ownership of their health data, and instead healthcare providers act as custodians of the data, responsible for its protection and appropriate use (Robin). Patients have rights to access and request corrections to their data, but legal ownership and control typically resides within the institution that collects and stores the data (Robin). Because of this, hospitals, research centers, and commercial partners often treat these datasets as institutional assets which can be shared with private companies or used for AI development without patients having control over how their information is used.

This leads to a question: should patients share the benefits or profits of AI systems that are trained on their data? When tech companies develop AI tools that predict the risk of cancer, identify types of tumor or optimize treatment plans, they are able to generate millions of dollars in revenue. Software solutions for cancer prediction and treatment optimization generated 1.39 billion US dollars in revenue in 2023 (“AI in Oncology Market Size, Share & Growth Report, 2030”). However, the individuals who provided the data essential for these achievements rarely receive any recognition or compensation (AIwithChris). This creates an ethical imbalance where the patient bears the risks of their own privacy, while organizations benefit financially. This imbalance is significant in oncology, as AI systems are built using large datasets from community hospitals that serve vulnerable individuals.

Because of the growing imbalance in profit between companies and patients (data providers), some studies suggest that patients should have a share in the economic benefits of AI innovations developed on their data (Tajabadi et al.). A “data dividend” model is an example of a way to compensate for the data the companies obtained. A data dividend refers to the idea of financially compensating patients for the use of their personal data, such as through the reinvestment of profits from AI tools into the public communities that contributed to the dataset (“The Data Dividends Initiative”). This type of approach will be able to increase the trust and support received by the public for data-driven research. Companies such as Folia Health have already implemented this data dividend model, compensating participants whose data is provided to AI-driven healthcare tools. Folia’s platform is used by patients and caregivers in order to track health experiences in home settings. They have introduced “data dividends” as part of their research program, where participants who opt in and submit data regularly for research are able to earn payments up to \$48 per year (Folia Health). This model is a great alternative to previous systems where data provided by patients are not acknowledged or compensated. By distributing a part of the profits gained from patient involvement back to the contributing population, Folia is

able to build trust and encourage participation among users who regularly track their health data. Although Folia Health is not in the oncology industry, this example shows how a data dividend model could be used in cancer research organizations and companies where patient participation is crucial. If major oncology AI developers were able to adopt a similar compensation system, patients could feel more acknowledged and create a better relationship between the company and patients. This could also help reduce the ethical gaps in consent and justice by making sure that communities contributing to the health dataset receive benefits in return.

Conclusion

As Artificial Intelligence continues to affect the health and oncology industry, consent is an essential requirement for ethical research in cancer. AI technologies' dependence on large collections of patient data raises several questions about control, transparency, and the respect for the patients' autonomy to be addressed as ethical priorities. Without clear communication between organizations and patients, patients will lose trust with their personal health information, causing difficulty in further developments in research and healthcare for other patients. Therefore, the development of AI must be combined with ethical consideration and social responsibility. Innovation in cancer research cannot succeed if it increases the existing inequalities or ignores the opinions of patients whose data AI-driven research rely on. It is important that AI systems must be developed to promote equity and respect for the patients' rights, making sure that benefits are shared widely rather than just single organizations and companies. Including patient-focused consent models such as dynamic consent and strengthening protections for the use of data are important in order to reach this goal. These methods will build the social trust needed for the continuation of participation in research as well as protect the autonomy of patients. Finally, the future of AI in oncology will heavily depend on the balance between the technological development and the consideration of social justice and ethical issues that arise. By doing so, cancer research will continue to develop while it supports fairness and respect for all patients.

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Martin Luther: The Overlooked Champion of Freedom in 16th-Century Europe

By Ashwin Narayan

In his seminal work *The Leviathan*, the English philosopher Thomas Hobbes defined freedom through a narrow lens, as “the absence of opposition.” In contrast, the Oxford Dictionary imbues freedom with a more personal dimension, denoting it as “The state or fact of being free from servitude, constraint, inhibition, etc”. This more individualistic notion of freedom gains philosophical grounding in Philosopher John Locke’s *Second Treatise of Government*, where he asserts that “each person is endowed with certain unalienable rights — that among these are life, liberty, and property”. However, while philosophers like Hobbes and Locke laid the theoretical foundations for freedom, nearly a century prior, a revolutionary figure embodied these and other ideas of freedom in action: Martin Luther.

Through ideas that reshaped belief, identity, and power, Martin Luther arguably did more to enlarge freedom than any other figure in Early Modern Europe. Specifically, he broke the Church’s monopoly on religion, enabled broader literary access through the vernacular, and laid the foundation for Germany’s nationalist movement. In doing so, Luther not only redefined the bounds of liberty, but additionally established a legacy of emancipation that transformed the world.

To fully understand Luther’s impact, it is helpful to examine freedom through the lens of Isaiah Berlin’s essay *Two Concepts of Liberty*. In this essay, he defines liberty in two senses: negative liberty, which he describes as “the degree to which no man or body of men interferes with my activity,” and positive liberty, which “derives from the wish of the individual to be his own master”, emphasizing self-determination and agency.

In exploring the degree to which Martin Luther expanded freedom of thought, we first must examine the religious context that repressed this freedom. In the aftermath of the Western Roman Empire’s collapse, the Catholic church emerged as both a spiritual and political authority. Initially a unifying moral force, it quickly evolved into an institution of control, enforcing strict doctrine through mechanisms like the Inquisition. Furthermore, by keeping the bible in Latin and asserting that salvation occurred only with it, the Church established an elitist hierarchy, indoctrinating the common people to believe in their divine-like nature. This absolutist power left little room for individual thought and free will.

Therefore, Martin Luther’s fight against the Church marked a radical departure. A theology Professor from Germany, Martin Luther disagreed with the church on a variety of topics, most notably the selling of indulgences—allowing the common people to pay for the forgiveness of sin— and the Church’s monopoly on spirituality. In response to these transgressions, Martin Luther nailed his 95 theses to the Wittenberg Church’s door. Embedded within this list were a set of beliefs that promoted religious emancipation, exemplifying Berlin’s notion of ‘negative liberty’. Importantly, Theses 6, which stated “The pope cannot remit any guilt, except ... showing that it has been remitted by God;” and Thesis 1, which stated “When our ... Master Jesus Christ said, ‘Repent’ (Mt 4:17), he willed the entire life of believers to be

one of repentance”, laid the foundation for the development of two separate religious doctrines: Sola Scriptura, which supported the Bible as the primary religious authority, and Sola Fide, a belief that salvation was attainable by faith alone. These two doctrines transformed the 95 theses into a powerful ideological source, one which restored the individual's religious autonomy and reignited the freedom of thought that the Church had extinguished. By enabling people to explore religious freedom and consequently initiating the Protestant Reformation, Luther echoed Berlin’s idea of positive liberty, as he empowered individuals to ‘achieve’ agency.

Even centuries later, European historian Gerald Strauss highlights how Luther’s theology “Liberated people from false piety”, enabling them to have closer, more personal relationships with God. By liberating people from a false sense of security within religion, Luther additionally enabled people to pursue their own form of self-government and subsequently, attain greater autonomy.

Not only did Luther’s leadership play a role in religious freedom, it also enabled cultural emancipation through fostering both intellectual empowerment and the development of a unifying cultural identity.

Luther fostered intellectual empowerment primarily via the spread of his 95 theses. Its integration into society, through the printing press, led “Luther’s thirty publications [to sell] well over 300,000 copies”, hinting at its usefulness as a unifying tool (Eisenstein 303). Aside from enabling collectivity, this mass dissemination of knowledge broke the church’s intellectual monopoly on religion. Tying back to Berlin, Luther ‘freed’ people from intellectual stiflement. Equally important, Luther translated the Bible from Latin to German, enabling the common man to read scripture directly. In fact, historian Carter Lindberg notes that Luther’s translation of the Bible “was a stimulus towards universal education”.

Building on Luther’s intellectual efforts, he additionally laid the groundwork for the development of a new, culturally distinct identity. As literacy began to transform and people began to interact with scripture more directly, cultural expression began to change. Literary scholar Richard Strier notes a striking transformation in Post-Reformation literature, observing of George Herbert, a famous English poet, that “The most obvious thing to say is that devotion to the Virgin, so pervasive (...) in the medieval lyrics, is absent from [George Herbert]’s poem”. Instead, his writing is thought of as “more simplistic, emphasizing the individual soul.” This literary development embodies Luther’s impact beyond theology: promoting a culture grounded in introspection and individualism.

In Luther’s translation of the Bible and disparagement of religious literature, he fueled self-reliance and inspired people to have courage. Consequently, Luther instilled the first notions of ‘enlightenment’, defined as “Man’s emergence from his self-imposed immaturity”. Ironically, Philosopher Immanuel Kant defined this term nearly 200 years after Martin Luther’s death. Yet, through his actions, Luther embodied Kant’s vision of enlightenment centuries before its cultural significance.

Through catalyzing Germany’s nationalist movement, Luther enlarged the conception of political freedom as well, which is defined by Britannica as the right of individuals to participate

in government. In Luther's seminal work *To the Christian Nobility*, he "linked the specific problems in which he had become embroiled with the broader political issues embodied in the Gravamina of the German estates...". In particular, he endorses the idea of *summus episcopus*, where ruling princes would act as highest clerical authority within their realm. This laid the groundwork for state churches, supporting Germany's growing nationalism. Additionally, through writings and translations that valued German language, Luther provided the framework necessary to fuel German nationalistic sentiment. The catalyzation of this independence movement would result in the Peace of Augsburg, enabling Germany to separate from the Roman church and pursue self-determination.

When examining Luther's influence, it is notable that he provided an intellectual and social framework for other figures who enlarged freedom. This can be proven by exploring the interconnectedness between Luther and John Locke, another figure who greatly expanded freedom. Most evident of Luther's enlargement of freedom is his efforts to expand religious freedom, through defying the Church and emphasizing individual autonomy. A century later, Locke inherited this religious setting, which he expanded upon in his essay *A Letter Concerning Toleration*. In this essay, he secularizes Luther's concept of religious freedom, applying it in his political belief that "the care of souls is not committed to the civil magistrate, any more than to other men." Thus, through this transformation from Luther's theological dissent to Locke on political autonomy, Locke exemplifies how Luther laid the framework for further expansion of freedom.

Despite his undeniable influence, Luther is not without his flaws; In his *Treatise on the Jews and Their Lies*, he expresses hatred towards the Jewish faiths, denigrating Judaism as a religion filled with 'devils', calling for the plundering of their homes, even scapegoating them as public enemies responsible for destruction.

To address this anti-semitism, it is important to understand Europe's broader discriminatory climate. As historian Mark Edwards writes, Luther was "so conventionally, so traditionally intolerant of the Jews", rather than egregiously so. While this does not justify his actions, it contextualizes Luther's actions under the broader failings of this era. Historian Geraldine Heng actually refers to this era as one of "race-making", a process of developing techniques to racialize one another. Therefore, though Luther's racism is undeniable, it should be viewed as quite ordinary within the context of his time.

When assessing Luther's global legacy of emancipation, his global influence stands out. The World Christian Database writes that close to 800 million Protestants live around the world today, spanning more than 80 countries. This statistic highlights the exponential growth of Protestantism, serving as a testament to how Luther's efforts towards religious autonomy have transcended time and geography.

Even the Catholic Church, once his fervent opponent, acknowledges his influence. Historian Jaroslav Pelikan notes that "The Second Vatican Council (1962-1965) accepted a number of Luther's theological points, and Pope John Paul II prays daily for a Catholic-

Lutheran reunification”, reflecting Luther’s role in transforming Christianity. Furthermore, this quote highlights Luther’s role in fueling religious unity and identity, key elements of cultural freedom.

On a more individual level, through his defiance of the church, Luther echoes later Philosopher Kierkegaard’s belief in the correlation between courage and freedom. Therefore, his depiction as the ‘German Hercules’, an image painted by Hans Holbein the Younger, is both justified and philosophically grounded. Importantly, Pelikan states that Luther’s image as the German Hercules persists to this day, which shows his enduring legacy of emancipation.

The term ‘freedom’ may appear simplistic at first, but history has shown it to be layered with nuance and complexity. This is what makes Martin Luther’s significance so profound; unlike other philosophers who merely theorized freedom, Martin Luther actively engaged with it. His defiance of religious tyranny, democratization of both literary and religious access, and expressions of national pride, enabled freedom to be expanded in its many forms. More importantly, his life demonstrates that freedom does not require grand actions, just feelings of conviction. For Luther, that conviction was based on belief, identity, and power. However, Luther’s influence in this regard extends to this era: anyone, no matter status or education, who acts with bravery and conviction can contribute to the enlargement of freedom. That message may be Luther’s greatest legacy.

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Alphafold and the Future of Computational Molecular Modeling By Eric Sun

Introduction

The microscopic world influences our daily lives in ways often unseen. Since the invention of the microscope in the late 1600s, our progress as a species in technological development has skyrocketed. Nowadays though, we have computers which have supercharged research efforts around the globe. This review summarizes the past, present, future of computational molecular modeling, going over how computational molecular modeling evolved into Alphafold, the current ongoing developments of Alphafold, and finally how it can be used in the future.

History of Computational Molecular Modeling

The use of computer modeling to understand molecular structures can be traced back to at least the 1970s. Using an electron density map derived from x-ray diffraction data via a Fourier transform, researchers were able to manually input the amino acid chain of Ribonuclease-A into the map. Following these procedures, the researchers calculated the predicted diffraction pattern and compared it to that of the experimentally determined pattern, adjusting the atomic coordinates until the R-factor was acceptably low enough. The R-factor, or residual factor indicates how well the crystallography model agrees with the x-ray diffraction data. As a result of this experiment, the backbone peptide chain of Ribonuclease-S was clearly defined due to high electron density, but some side chains weren't clearly defined. Hydrogen bonds also weren't able to be seen in the electron density map (Wyckoff et al., 1970).

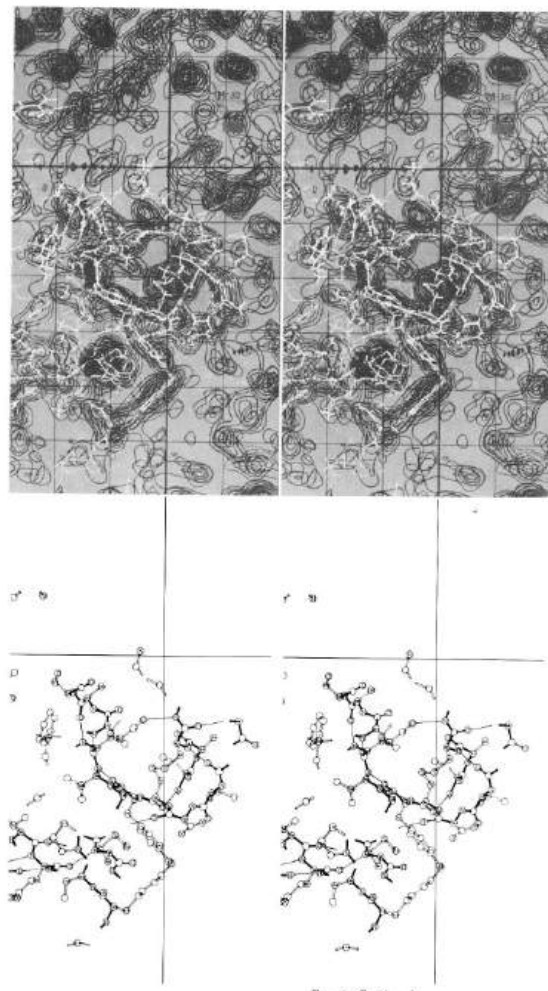


Figure 1: Electron Density Map of Ribonuclease-A (taken from Figure 4, (Wyckoff et al., 1970).

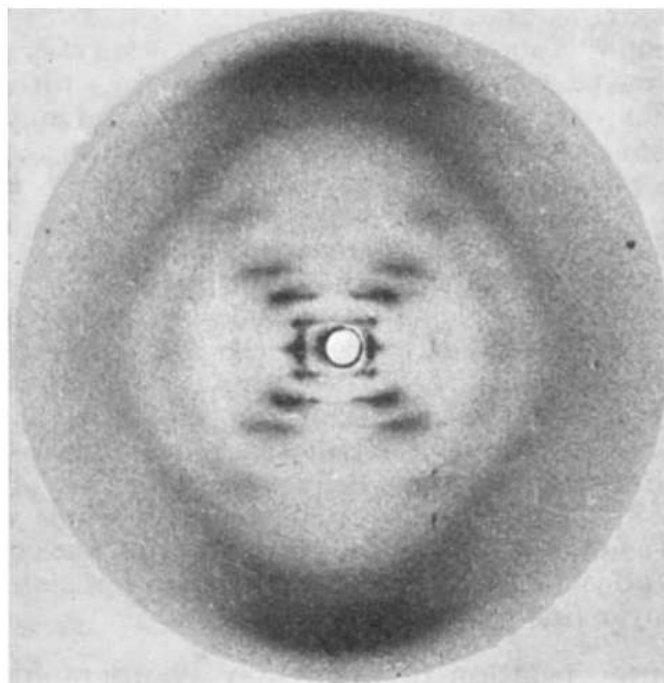


Figure 2: X-ray diagram of DNA (Taken from structure B, (Franklin & Gosling, 1953).

Overall, modeling molecular structures using this method is not completely accurate and depends on data, such as electron density, which may not be consistent. Further refining these methods, researchers used more refined methods of x-ray crystallography to determine the molecular structure of Ribonuclease-S based on the already determined fractured structure of RNase-A. Refining 3 different crystal structures of RNase-S at different pHs and along with a truncated peptide (S15 rather than S20, which is the full peptide), researchers were able to achieve a higher resolution of 1.6 Angstroms, compared to the previous 2.0 Angstroms reported in earlier studies. This was mainly due to new technologies and more refined crystalline structures as a result of better confined environments to synthesize the RNase-S Structure. As a result, researchers ended up with clearer, and more improved electron density maps than before. They were also able to find the active sites on the molecule, which was composed of the side chains of His 12, Lys41, Val43, Asn44, Thr45, His1 19, Phe120, Asp121, and Ser123, as well as a sulfate ion alongside them. (Kim et al., 1992).

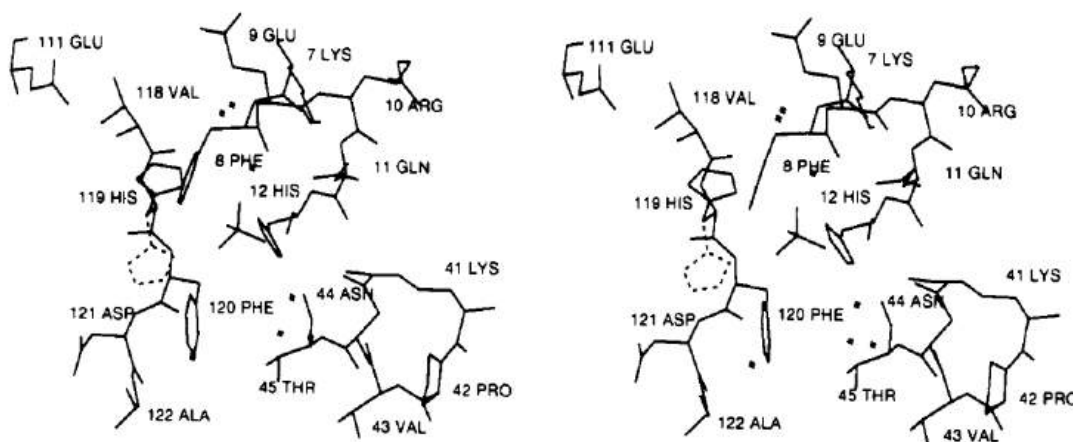


Figure 2: Stereochemical view of the active sites on Ribonuclease-S (Taken from figure 3, (Kim et al., 1992).

Later, with more and more methods of determining molecular structure arising, as well as us reaching the technological limits of physical methods, researchers decided to conduct a blind study, which compared the accuracy of different structure determining methods to that of x-ray crystallography, which was known to be accurate. This way, researchers wouldn't need to solely depend on crystallography in order to find the structure of certain molecules. So, 3 groups of difficulties were created: comparative modeling, threading, or ab initio. Comparative modeling utilized known structures that were close to the tested sequence. Threading, or fold recognition, did not have a clear close relative protein sequence, but could be classified as having a possible similar fold to a known sequence. Lastly, ab initio predictions did not rely on any known folds and were purely just relying on prediction. As a result, researchers found that when good templates were available for a structure prediction, models predicted correct folds during comparative modeling. Except, there were a few main issues. The models had trouble with aligning target sequences from the template onto the predicted fold structure, side chain orientations, and modeling of loops. With threading, some models were occasionally correct, even without homology of sequences. Threading techniques involve detecting the similar chain of amino acids and then "threading" it into the predicted model and the fitness of interactions are then calculated using a fitness function. Despite this, the fitness functions were often inaccurate and the alignments were frequently incorrect. Ab initio predictions were the hardest to predict, with no data to go off of. Some models yielded rough topological models, but nothing of significance. This experiment as a whole painted a picture on where modern technology was currently at with protein structure determination. This experiment was one of the first CASP experiments conducted, allowing researchers to know how well their prediction models fared against unknown protein structures, creating a standardized benchmark for evaluation and driving innovation in the field. (Moult et al., 1995).

The question of protein folding describes the ways on how a protein's amino acid structure dictates its 3D structure. The initial hypothesis for the mechanism behind protein

folding was that the configuration of a protein desired to be as thermodynamically as possible, in its most stable state. Researchers also believed that folding was a product of many little chemical interactions, such as hydrogen bonding, ionic interactions, and van der Waals forces. But, by the 1980s, through statistical mechanical modeling, it was discovered that hydrophobic interactions were integral in driving proteins into compact folds. Advances in protein structure science such as laser temperature jump methods, ϕ -value mutation methods, hydrogen exchange, peptide test systems, and single molecule techniques allowed researchers to investigate further into foundational folding processes and intermediate states. During the 1980s-90s was when first attempts to integrate computer based methods into protein structure determination. Researchers attempted to use force fields and Monte Carlo methods for small peptides. Force fields are mathematical models that estimate the potential energy of a protein by using bond lengths, angles, torsions, van der Waals forces, and electrostatics. Monte Carlo methods are random algorithms that explore protein conformations by making random changes and evaluating them using force fields. These proteins are then accepted or rejected based on their potential energy. In the early 1990s, homology modeling, threading, and sequence alignment became more useful thanks to growing databases of protein structures. CASP (Critical Assessment of Structure Prediction), launched in 1994, spurred great improvements in methods for structure determination. In 1968, Levinthal raised the question as to how proteins fold so quickly despite there being such a vast number of conformational possibilities.

As a result, different models emerged in order to answer this question. The diffusion collision model, nucleation-condensation, foldon, and the Zipping and Assembly (ZA) mechanisms were some such models. These models all generally outline how during the process of protein folding, they all start by reaching conformations of smaller units, eventually shaping into the whole folded protein. Later, the concept of funnel-shaped energy landscapes became widely accepted, stating that proteins avoid random conformations by defaulting toward lower energy states. Aside from prediction models, computer simulations of physics-based models were becoming increasingly useful for structure prediction because it allowed researchers to have a better understanding of protein folding aside from bioinformatics. Simulations like Folding@home allowed for large scale sampling of folding events. Methods like replica exchange molecular dynamics (REMD) enabled simulations of small proteins to increase accuracy. The Zipping and Assembly Method (ZAM) combined fragment simulations with assembly in order to predict correct folds for small proteins up to around 2.5 Angstroms. As a result of these improvements, the issue of protein folding was no longer as large of a problem as before, and computational methods (especially database and physics based methods) were correctly predicting the structures of smaller proteins. Theoretical frameworks also gave researchers a better picture of how folding works. (Dill et al., 2008)

The data from cryo em is the main source for what AI structure determination software is trained on, which makes it very important to the development of deep neural networks for predicting the structures of proteins. Cryo-EM stands for cryo-electron microscopy, and uses electron detectors and image processing to yield a density map to determine atomic structure. In

contrast to that of X-ray crystallography and NMR Spectroscopy, which require large samples of pure substances, Cryo-EM only requires much smaller samples of less pure substances, given that the sample has been frozen in vitreous ice. Cryo-EM also does not require crystallization. Integrating 3D reconstruction, which is the use of 2D images from different directions to produce a 3D model, and Cryo-EM, researchers are able to identify the positions of atoms in molecules. Despite these benefits, Cryo-EM has only been able to produce low resolution density maps for large molecules. Despite this, over recent years, the resolution of Cryo-EM density maps have dramatically increased due to advances in image processing and electron detectors. For example, direct electron detectors reduce noise and radiation, allowing it to detect electrons with increased accuracy. This new technology trumps the previously used photographic film in both quality and efficiency. As a result of these breakthroughs, Cryo-EM now rivals that of X-ray crystallography, with some cryo-EM structures achieving a resolution of less than 5 Angstroms and some close to 3. A couple notable examples of these are of the TRPV1 structure, with a resolution of 3.8 Angstroms, and the cytoplasmic ribosome of *Plasmodium falciparum* at a resolution of 3.2 Angstroms. Even the smaller, asymmetric molecule γ -secretase was also solved at a 4.5 Angstrom resolution. In the future, Cryo-EM will continue to produce structures with much higher resolution, making the determination of protein structures much less time consuming and more efficient. (Bai et al., 2015).

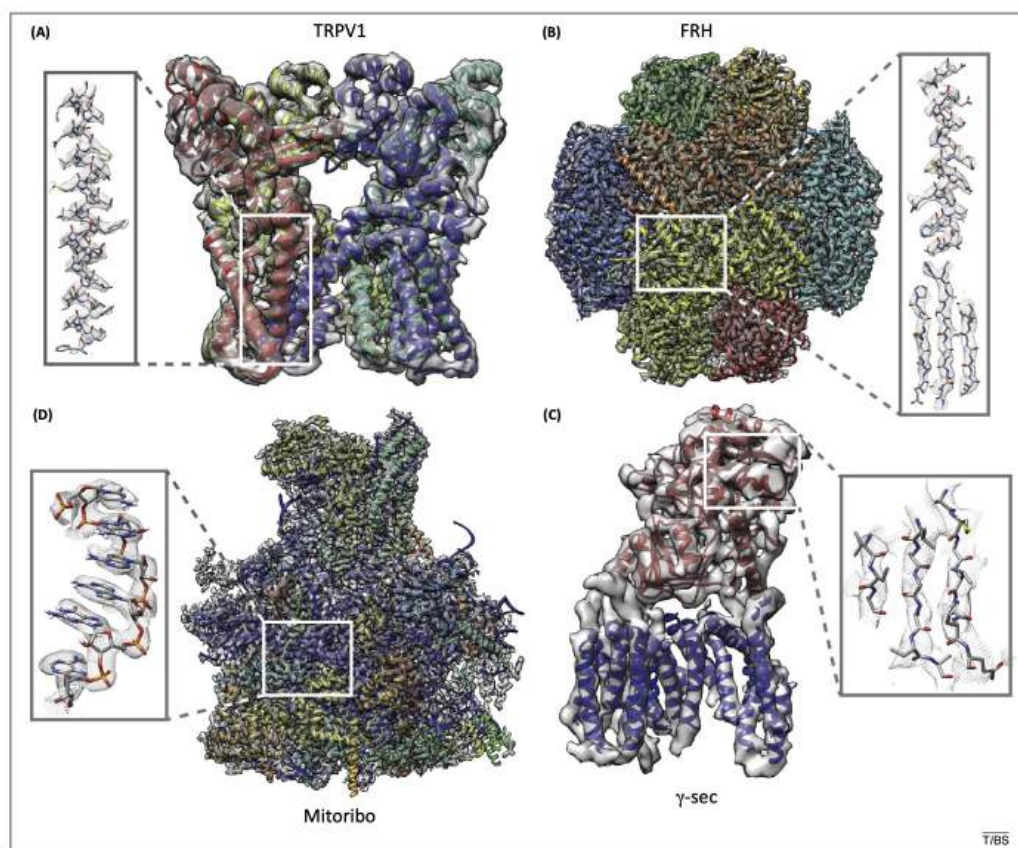


Figure 3: Cryo-EM maps of TRPV1, FRH, Mitoribo, and γ -secretase (Taken from figure 4, (Bai et al., 2015).

Active Developments and Innovations of Alphafold

Deep learning is a class of machine learning where computational models learn directly from raw data, using many levels of abstracted layers rather than through manually designed learning structures. Raw data is first transformed into These deep learning methods use layers of non-linear transformations stacked in multiple layers so that computers are able to understand multiple layers of abstraction, from raw data to high level objects. Supervised learning trains the neural network on massive datasets using stochastic gradient descent, adjusting weights on each of the network's countless parameters until the desired performance is reached. Back propagation is a method that adjusts each weight in the network to achieve the desired output. The forward pass computes the predictions of the network, and the backward pass computes how wrong that prediction was and adjusts the weights. Combined with supervised learning, these two methods allow the network to 'learn.' Convolutional neural networks are designed to process data that comes in arrays, like images and video. Recurrent neural networks are more suited for data that is sequential, such as speech or text. They are trained using back propagation and enable features such as machine translation, speech recognition, and text generation. While these methods and concepts have made significant breakthroughs in artificial intelligence in recent years, there is still more to what AI can be capable of. Unlike humans, who can learn from very few examples, training neural networks still requires large labeled datasets, but for AI to improve and achieve true reasoning, they should learn like humans. Unsupervised and semi-supervised learning could possibly make more advancements in the future, discovering patterns from unlabeled data, and eventually moving closer towards human-like intelligence. (LeCun et al., 2015)

Around 2021, Google's deepmind released Alphafold 2, a complex neural network capable of accurately predicting the structure of a single protein using its amino acid sequence. Alphafold is trained on certain protein databases like the Protein Database (PDB). By this time, only about 100,000 protein structures have been experimentally determined, out of the billions possible. This is because the physical methods of determining their 3D structures are resource and time intensive. Also, predicting a protein's 3D structure from its amino acid sequence has been an unsolved problem for many years, given the vast possibilities of conformations. Using computer based approaches to structure prediction, there still are challenges to overcome. For example, homology modeling requires a similar known structure, which isn't always available. Purely physics based simulations were also very computationally expensive and not always accurate. Despite this, due to innovations in the Deep Learning architecture of Alphafold 2, it outperformed all other computation methods in CASP (Critical Assessment of Protein Structure Prediction), which is a standard for structure determination, predicting the correct structure for many proteins with known structures. It includes an evoformer within its architecture, and also recycles its predictions to refine them. Alphafold not only trained on PDB structures, but also trained on its own confident predictions, allowing it to expand and generalize beyond its given data. Alphaold also reached almost experimental grade accuracy, with a median of about 1 Angstrom. (Jumper et al., 2021).

AlphaFold 3 was released in 2024, and was a more new and improved version of AlphaFold 2 in the sense that it could more accurately predict the structures of different proteins as well as model the interactions between the proteins and different ligands, ions and nucleic acids. AF2 couldn't handle these molecules, but specialized tools such as RoseTTAFold, and docking, except that they had lower accuracy and weren't easily able to be generalized. AF2 also sometimes produced physically impossible outputs, alongside with the same results in ligand docking. Alongside that, computer models were prone to hallucinations, could only make static predictions without dynamic changes, and couldn't generalize across the interactions of many different molecules. When AF3 was released, it had a better, unified framework, where one model predicts all interactions between proteins, ligands, ions, and nucleic acids. Instead of an Evoformer, AF3 uses a Pairformer module, which simplifies its processing by reducing the emphasis on multiple sequence alignments. AF3 also runs on a diffusion model and learns structures of molecules via denoising at different noising. It outperforms almost all specialized models in almost all categories as well. (Abramson et al., 2024).

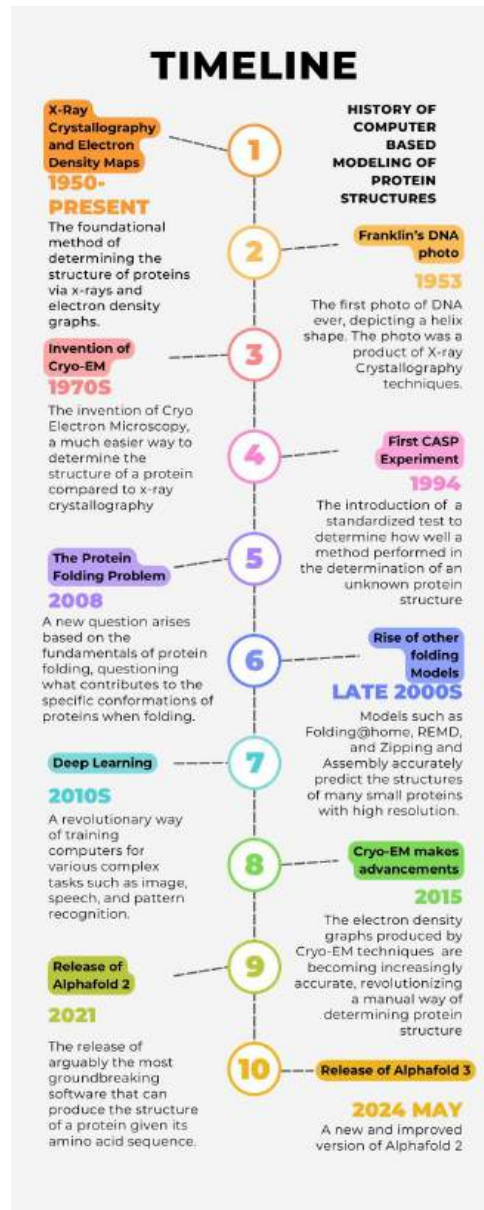


Figure 4: Breakthroughs that lead up to the development of AlphaFold 3.

Currently, AlphaFold 3 reigns as the most accurate software for predicting and modeling protein structures. It outperforms all other specialized models in almost every aspect. It is also being used as a product and a tool, being sold to pharmaceutical companies and biotech startups, such as Eli Lilly, Novartis, and Isomorphic labs by Google. Since this software is being sold to other companies for the purpose of designing proteins to target specific illnesses, in the future, more similar events are bound to happen. As technology advances, and AlphaFold becomes better, more companies will possibly engage in this endeavour of curing diseases by engineering drugs using AlphaFold. This software has immense potential, possibly allowing people to cure diseases such as Alzheimer's, Parkinson's, and Cancer. Combining AlphaFold with certain technologies such as CRISPR can speed up development and unlock new possibilities. In order

for this to happen though, AlphaFold needs to develop beyond its current constraints of the limited interactions it can simulate. In 2024, AlphaFold received the Nobel Prize in Chemistry, which shows the monumental potential it has. Thus, AlphaFold will likely make a big impact in the future in not only the field of Science, but even daily life.

Future Applications of AlphaFold

Despite the fact that physical methods such as X-ray crystallography and NMR Spectroscopy have been around since around the 1950s to 1970s, researchers have created AlphaFold only just now due to various reasons. It has taken years to develop a sufficiently large enough database for these models, as well as years for technology to develop. Computers in the past wouldn't have been strong enough to run or much less train these models. Even then, ideas of such methods haven't been developed due to advancements that have not yet been made. Some of the most influential advancements on the road to AlphaFold have been the continuous effort of researchers to physically determine the structures of hundreds of thousands of proteins by hand to build up the protein database, the development and application of Cryo-EM, which is what most of the data that AlphaFold is trained on, and neural networks, serving as the blueprints for it.

The development of AlphaFold has been instrumental in the field of science, no matter the field. To describe it as a great invention is an understatement. It is a groundbreaking development capable of advancing science at an unparalleled pace. There are seemingly unlimited possibilities that AlphaFold can create. Researchers can use it to do anything that concerns the determination of shapes of proteins.

Drug developers can use AlphaFold to not only design new drugs, but test known ones on different environments, to see how they react to different things around them. It is a valuable tool which can be used to experimentally test ideas in a short amount of time, saving precious resources and time, as well as testing small ideas that would otherwise take much longer to set up. For example, researchers would be able to take a diabetes drug, and test it on a lot of other proteins in order to see how it does and make conclusions from that. It would be like taking one known substance and learning everything about it through simulations. AlphaFold could be the software that exponentially increases the knowledge that scientists have about proteins and other molecules and substances a second time.

Some possible applications of AlphaFold would be using it to deal with plastic pollution, using it to develop a new plastic degrading enzyme. First, databases would be searched to find different protein sequences in polluted areas. Then, AlphaFold is used to predict the structures of candidate enzymes and compare these structures to known plastic degrading enzymes to find similar active sites. Databases are searched through because these protein sequences could help provide similarities in structure, which then are similar in function to the needed proteins, as well as containing the possibility of discovering a new protein sequence that can degrade plastic. Searching through untested protein structure opens a new window of opportunity, since their functions are largely unknown.

Another potential application of this technology is to use AlphaFold to understand how specific mutations in cancer genes (such as p53 or BRCA1) disrupt structure. First, AlphaFold would be used to predict the mutant structure, and then quantify the structural distortions, and suggest how these mutations might affect DNA repair or apoptosis (programmed cell death). Essentially, the mutations will be mapped by comparing the mutated structure to a healthy structure.

AlphaFold could also be used to design antidotes to venom poisons. First, the protein sequence of the target venom would be selected from a database, and then use AlphaFold to model this sequence and identify the toxic sites. And then, neutralizing antibodies or peptide blockers would be modeled using docking tools. Researchers could also predict mutations in certain diseases, why the immune system begins attacking itself with certain diseases and the causes of rare genetic diseases. AlphaFold enables researchers to model these diseases, and therefore make it easier for them to identify the causes and effects of them.

Some of the largest limitations for AlphaFold is that users aren't allowed to choose and model custom ligands to bond to the chosen protein sequence. AlphaFold primarily predicts static structures, which means that it struggles with dynamic processes like conformational changes or interactions with other molecules. Additionally, it can also struggle with correctly modeling regions where alignment data is sparse, such as protein interfaces or disordered regions. AlphaFold also doesn't account for factors like ligands, ions, or post-translational modifications, which can significantly impact protein structure and function. Again, AlphaFold only predicts structure, and is very specialized in that, but that also means the only thing AlphaFold is really good at is predicting structure. So, it is not very good at doing anything else. Whether it be predicting stability or function of a certain molecule. Since AlphaFold is a neural network, it needs to be trained on data, which is something that may not always be available. Therefore, AlphaFold may also not be as proficient in modeling the structures of new or synthetic proteins.

Conclusion

Despite its limitations, AlphaFold is still an amazing tool, and it is also a great stepping stone for more advanced tools that will continue to improve humanity's understanding of the world. Many technological breakthroughs have contributed to the creation of AlphaFold, but arguably the most important ones are Cryo-EM and deep learning. In the past few years, AlphaFold has undergone significant changes in its architecture, improving its ability to predict molecular structures and keeping its place as king of computational molecular modeling. As AI continues to advance, AlphaFold will break through its current limitations. Its improvements will and already have drawn companies to the use of AI-assisted drug development, such as Eli Lilly and Novartis. AlphaFold can be used to identify and possibly create enzymes to degrade plastic, neutralize poison, and even help cure cancer. AlphaFold has unlocked a door to a vast array of amazing opportunities which we must use wisely.

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ACL Injuries and Reinjuries in Adolescent Athletes By Ania Jalori

Abstract

This literature review identifies what factors contribute to ACL injuries and reinjuries in adolescent athletes, and how the risks can be reduced. This literature review uses sources found from PubMed, ScienceDirect, Google Scholar, and other university institutional websites. The sources were focused on ACL injuries and reconstruction in athletes, specifically. The sources were analyzed and compiled to present information regarding ACL reconstruction, factors of injury, and return-to-sport testing. The findings indicate that the risk of ACL injuries can be reduced by incorporating preventive training and designing programs for athletes that focus on working all muscle groups. After an ACL reconstruction, a key reason for reinjury is rushing back into intense activity before your body has fully healed. There are controversies over the exact time for return-to-sport, so it is important that athletes' rehabilitation programs are designed based on their unique needs to reduce secondary injury risks.

Introduction

Anterior cruciate ligament (ACL) injuries are one of the most common knee injuries, with an estimated incidence of 250,000 per year, and have seen a rise amongst adolescent athletes (*Four Reasons for Rising ACL Tears and Other Knee Injuries* | Northwell Health; *ACL Injuries Are on the Rise, but Can They Be Prevented?*; *ACL Tears in Children* | Johns Hopkins Medicine). The injury rate among 14-18-year-olds has increased by 147.8% in the last 10 years (*Four Reasons for Rising ACL Tears and Other Knee Injuries* | Northwell Health; Grindem et al.). This is likely multifactorial, with a key factor being an increase in the activity and rigor of sports.

The ACL is a ligament that is attached to the femur and tibia inside the knee joint and controls how far the tibia can move forward with any given force (*Anterior Cruciate Ligament (ACL) Injury or Tear*). The ACL plays a crucial role in the overall stability of the knee, especially during sharp movements. The ACL can be injured in many different ways, including sports, jumping, changing direction quickly, or direct contact (*ACL Injuries Are on the Rise, but Can They Be Prevented?*; *ACL Tears in Children* | Johns Hopkins Medicine; *Anterior Cruciate Ligament (ACL) Injury or Tear*). However, more than 70% of injuries are noncontact (*ACL Tears in Children* | Johns Hopkins Medicine). Often, ACL injuries are accompanied by other knee injuries, such as meniscus tears and damage to other ligaments (*Anterior Cruciate Ligament (ACL) Injury or Tear*). Most ACL tears are repaired with surgery to maximize the chances of athletes being able to return to sports (*ACL Injuries Are on the Rise, but Can They Be Prevented?*; *ACL Tears in Children* | Johns Hopkins Medicine; *Anterior Cruciate Ligament (ACL) Injury or Tear*). ACL injuries are very serious and can be career-ending. “After ACL reconstructive surgery, an estimated 82% of individuals return to sport participation; however, only 63% return to their preinjury level of sport participation, and only 44% return to competitive sport” (Padua et al.). Another concern with ACL injuries is the risk of knee

reinjuries or a secondary ACL injury. “Up to 30% of young active patients who undergo reconstruction suffer a second ACL rupture” within the first few years of their initial surgery (Grindem et al.). Many factors affect the ability of athletes to return to their sport and avoid re-injury, including physical health, demographics of the athlete, time of return to sport, rehabilitation methods, and sport type (Beischer et al.; “Younger Age of Primary ACL Injury, Decreased Time to Return to Sport Significantly Increases Risk of Secondary ACL Injury in Adolescent Athletes”; Syed et al.).

This literature review aims to investigate what factors contribute to ACL reinjury and what preventative measures can be taken to avoid them. Through the analysis of many studies, this review will outline elements that prevent secondary ACL injuries in adolescent athletes and how we can reduce those risks.

Methods

In this literature review, I compiled information from various sources to identify the causes of ACL injuries and how to avoid secondary injuries. These searches were performed on PubMed, ScienceDirect, Google Scholar, and other university institutional websites. I originally started with using the keywords “injury prevention” and “rehabilitation techniques”, with a specific focus on sources that are related to sports and athletes. Later on, I narrowed down my keyword search to “ACL injury factors” and “ACL reinjury factors” with specifics of “return to sport” and “athletes”. The search results were prioritized in order of results shown, and both review sources and original studies were used.

Review

Ways to reduce ACL injuries

Key factors in preventing ACL injuries include preventive training techniques to ensure the body remains fit. Several studies suggest that taking a proactive approach to ensure an athlete's body is prepared for intense activities is crucial in preventing injuries (*ACL Injuries Are on the Rise, but Can They Be Prevented?*; *ACL Tears in Children | Johns Hopkins Medicine*). Not only should the athlete work on training the knee, but also surrounding muscle groups like the hips, quads, and hamstrings (*ACL Injuries Are on the Rise, but Can They Be Prevented?*). Programs that focus on neuromuscular control and biomechanics can help prevent injuries by training the body to move in a way that reduces the strain on the knee joint (*ACL Injuries Are on the Rise, but Can They Be Prevented?*; Padua et al.). An analysis done by Petushek et al. showed that injury prevention neuromuscular training (NMT) programs can reduce the risk of an ACL Injury from 1 in 54 to 1 in 111 in young female athletes (Petushek et al.). Conversely, when combined together, neuromuscular multicomponent training programs can reduce ACL injury rates in females by up to 75% if implemented a few times a week for 15-20 minutes (Padua et al.).

Another key component in the rise of ACL injuries recently has been the increased physical demands placed on adolescent athletes. Athletes today are expected to train and perform at higher levels than ever before, but their bodies are not yet as developed for that. Adolescent

athletes' bodies are still growing at this time, so very rigorous activity can put a lot of strain on them physically and mentally. Players are participating in more demanding and frequent training sessions to enhance their competitiveness in their specific sport. Specializing in a single sport from a young age puts stress on the same part of your body over and over again, increasing the risk of injuries. Making sure not to overexert your body and maintain fitness throughout will be significant towards the prevention of ACL injuries (*Four Reasons for Rising ACL Tears and Other Knee Injuries* | *Northwell Health*; Childers et al.). This doesn't mean that athletes shouldn't train intensely at all, just that they should train appropriately. Excessive and rapid increases in training loads can be more likely to be a cause of ACL injuries than physically hard and appropriate training (*Four Reasons for Rising ACL Tears and Other Knee Injuries* | *Northwell Health*; Childers et al.; Gabbett). Appropriate training is actually beneficial and can protect against injuries (Gabbett). Since 70% of ACL injuries are noncontact, body fitness is key to reducing the risks (*ACL Tears in Children* | *Johns Hopkins Medicine*).

Some external factors that impact the chances of ACL injuries can be demographics and the level of sports. Female adolescent athletes have a greater risk of ACL injuries compared to males. Literature suggests this may be due to physique differences or hormones. Regarding female hormones, a connection has been found; there appears to be a correlation between a higher rate of ACL injury during a woman's menstrual cycle. The type of sport, level of sport, and sport affiliation are other contributing factors in high ACL injury rates. It has been found that the highest reported rates of ACL injuries happen to athletes who play soccer, football, and basketball. Soccer exhibited the highest number of injuries in females, and football in males. It has also been shown that there is an increased incidence of ACL injuries in adolescent athletes in club sports over school sports, with a relative risk of 3.94, due to competitiveness levels and sports specialization (Childers et al.).

ACL reinjury factors and risks

While ACL reconstructions are highly effective, athletes still face the possibility of reinjury after undergoing surgery. These factors can vary from pre-injury risks, pre-surgery rehabilitation, post-surgery method of rehabilitation, RTS, etcetera. This section will evaluate and report on different studies that investigate varying factors.

An athlete's post-surgical rehabilitation can be conducted at the athlete's home, referred to as home-based rehabilitation (HBR), or in a clinic, called supervised rehabilitation (SVR). A study conducted by Syed et al. aims to compare home-based versus supervised rehabilitation methods to determine which has a higher return-to-sport rate and whether the risk of reinjury differs between the two methods. They split a group of 60 high-risk sports athletes who have undergone ACL reconstruction by the same surgeon into 2 equal groups (15 female and 15 male). One of these groups participated in an HBR program, while the other underwent an SVR program; however, both methods aimed to help the athletes return to their sport. There were no significant differences found in regards to weight distribution in stance, squats, hip abductor and adductor force, and asymmetry measurements between the 2 methods. Additionally, both SVR

and HBR groups had a 3.3% overall chance of reinjury (contralateral ACL injury rate was higher in SVR than in HBR). However, the SVR group had 76.6% of athletes return to their sport at pre-injury levels compared to only 53.3% in the HBR group (Syed et al.; Uchino et al.). Another study was done to address the fact that many studies found no significant difference between supervised and home-based rehabilitation after ACLR. They believed the function of the nonoperative knee, hamstring strength at deep flexion, and neuromuscular control had been overlooked. They addressed these gaps by not using the Limb Symmetry Index (LSI) to measure progress, as it can be misleading when both limbs are weak overall. Instead, they compared all measurements between operative and nonoperative knees to investigate differences in outcomes after ACLR between SVR and HBR. The study found that the SVR group displayed greater muscle strength, better neuromuscular control, and higher patient-reported knee function than the HBR group, concluding that supervised rehabilitation may offer more benefits than home-based rehabilitation (Syed et al.; Uchino et al.; Rhim et al.).

While this may seem out of one's control, the younger the athlete is at the time of their first ACL injury, the higher the chances of reinjury are. Each year prior to the primary ACLR increases, the rate of a secondary ACL injury decreases by 29% (“Younger Age of Primary ACL Injury, Decreased Time to Return to Sport Significantly Increases Risk of Secondary ACL Injury in Adolescent Athletes”).

Return-to-Sport (RTS) Timing Analysis

While all the factors discussed before are key in reducing re-injury, another major variable in the risk of ACL reinjuries is the timing of return to sport (RTS). Numerous studies have shown that the timing of an athlete's return to their sport after ACL reconstruction significantly impacts their risk of reinjury. When athletes attempt to return to their pre-injury level of activity, they substantially increase their chances of a secondary ACL injury. While there is no universal perfect timeline for everyone, as all bodies are different, there are some recommended guidelines to help facilitate the process of deciding when an athlete can return to their sport. Typically, either a conservative or accelerated approach is taken to the rehabilitation process. A conservative approach is characterized by a return to sport at 9 months, while an accelerated approach is described as one with a return to sport by 6 months. The rehab exercises are similar in both methods, but the accelerated approach advances the intensity of exercises faster than the conservative approach. A study concluded that there was no universally perfect timeline. It all depends on the athlete's needs and the nature of the sport. Similarly, there is no set return-to-play guideline that is considered the correct way. The only thing that is universal is that return-to-play decisions should be multidisciplinary and criteria-based in nature and consider a multitude of factors (Waldron et al.). However, other studies have found a correlation between a later RTS and a decrease in the risk of ACL reinjuries (Chen et al.; “Younger Age of Primary ACL Injury, Decreased Time to Return to Sport Significantly Increases Risk of Secondary ACL Injury in Adolescent Athletes”; Beischer et al.). A study by Chen et al. stated that a one-month delay in RTS decreases the rate of a secondary ACL injury by 17% (“Younger Age of Primary

ACL Injury, Decreased Time to Return to Sport Significantly Increases Risk of Secondary ACL Injury in Adolescent Athletes”; Chen et al.). Many experts say that the 9-month mark should be the baseline for allowing an athlete to return to their sport (Beischer et al.; “Younger Age of Primary ACL Injury, Decreased Time to Return to Sport Significantly Increases Risk of Secondary ACL Injury in Adolescent Athletes”).

Discussion

Anterior Cruciate Ligament (ACL) injuries remain one of the fastest-growing injuries among adolescent athletes, with an increase in both primary and secondary injuries. Previous research has identified factors that contribute to ACL injuries and reinjuries, and preventative measures that can be taken to avoid ACL injuries. Many studies have emphasized the importance of carefully structured rehabilitation programs and neuromuscular training in reducing these risks (*ACL Injuries Are on the Rise, but Can They Be Prevented?*; Padua et al.). Researchers have explored in depth the correlation of the time of return to sport with ACL reinjury numbers. The purpose of this literature review was to synthesize research to better understand the factors contributing to ACL reinjury, assess how to reduce risks, and determine how return-to-sport timing affects outcomes for adolescent athletes after ACLR.

ACL injuries and reinjuries

A study by Childers et al investigates which levels of sports and demographics have a higher risk of ACL injury. After compiling information from different sources about adolescent athletes, it is concluded that females have a higher risk of ACL injuries. Club sports have a higher risk of ACL injuries, and in general, soccer and football players see higher rates of ACL injuries (Childers et al.). While this could be true because of the nature of the sport, one factor to consider is the popularity of these sports. Football could make sense for men based on the very physical aspect of the sport, but soccer is one of the most played sports for females, and basketball is one of the most popular among men. If there is an increased number of athletes participating in these sports, it could skew the data to show higher reported incidences of ACL injuries in these sports. Another topic that wasn’t specifically discussed in this source, but could be a justification for the increased risk in club vs. school sports, is the length of participation. The season for club sports is often longer and multi-seasonal, which requires more frequent rigorous training than school sports might. The combination of the competitiveness of club sports and year-round activity in sports could justify the increased incidence level. Playing year-round means that athletes have less recovery time, which hurts their bodies and makes them more susceptible to injuries.

Return-to-Sport (RTS) Timing Analysis

Current research about the appropriate time of return-to-sport and how it affects the chances of secondary ACL injuries in athletes has many different sides. In the rehabilitation process, there are 2 main approaches: conservative and accelerated. There are many pros and

cons to each, and different studies have made different conclusions. The study by Waldron et al. claims that conservative rehabilitation is beneficial because it allows athletes to strengthen surrounding muscles through a slower rehabilitation; however, it takes longer for the knee to gain strength and can have higher financial burdens. On the other hand, the accelerated approach is good because an athlete can reach the desired result of going back quicker, but there is a higher risk in chances of another ACL tear (Waldron et al.).

Whereas this study officially concluded that both are beneficial for different people, there have been many other sources that show that not rushing the return to sport process has major benefits. Research has shown that the 9-month mark is a good average for an athlete to return to their sport, and a delayed return to sport can significantly decrease the chances of ACL reinjury (“Younger Age of Primary ACL Injury, Decreased Time to Return to Sport Significantly Increases Risk of Secondary ACL Injury in Adolescent Athletes”; Chen et al.). I believe that allowing an athlete more time for their body to recover after an ACLR is crucial and is worth the small sacrifice of the downsides of the conservative approach. Recently, the push to get athletes back to their respective sports quicker has proven to be negative by putting the athlete in danger of a reinjury. The popularity of the accelerated approach to rehabilitation might be hurting athletes' chances of being able to play their pre-injury sport safely.

Limitations

This review compiles many sources with many different sample data sets to make conclusions about ACL injuries, but this does have some limitations. First, many of the studies used have different designs, sample sets, age groups, types of athletes, rehabilitation protocols, and criteria, which means it is not possible to make generalizations that are guaranteed to apply to everyone. As mentioned throughout, each athlete's body is different, so what might be the case for one person is not assured to be the same for another. Second, the sample set of athletes varies, and not every sport and type of athlete may be represented equally among the studies. Lastly, no original studies were conducted, so information is limited to the literature that already exists.

Conclusion

ACL injuries are impacted by a multitude of factors, but can be prevented by implementing and prioritizing neuromuscular and multi-component training. Making sure to train all muscle groups, instead of only specialized training based on a specific sport, is key to lowering ACL injury and reinjury risk. It is also important to be aware of the type of sport that athletes are involved in, as very physical sports correlate to higher risks of ACL injuries. Especially now with the increased pressure on athletes to perform at higher levels than ever before, it is recommended not to rush back to their sport after an ACLR. Based on this study, it is recommended that adolescent athletes meet the return to sport criteria and incorporate injury prevention into their training.

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The Math Behind Gacha Games By Joowon Cha

Intro

Gacha games are video games that combine fun stories, missions and rewards with a gameplay element known as gacha. The word gacha refers to toy vending machines where you put in a coin to receive a toy. Gacha games allow players to purchase a random selection of characters, weapons or items—much like a toy machine.



One of the best examples of the gacha mechanic is Hoyoverse, creator of the popular games Genshin Impact and Honkai: Star Rail. Their gacha mechanic works by attaching levels to items and characters based on their rarity. For example, there are common 3-star items, rare 4-star items and super-rare 5-star items. Acquiring a 5-star character, similar to a strong hero in Genshin Impact, is very difficult, due to the extremely low odds of acquiring it—roughly 0.6% (6 in 1,000 tries). Because of this, the gacha games are determined by a high amount of randomness, in contrast to other games that allow players to earn all items simply through dedicated play.

To participate in the gacha, players must use in-game currency, like Primogems in Genshin Impact or Stellar Jade in Honkai: Star Rail. The player can collect in-game currency by completing quests, events, or daily collectibles in the game. Because rare items are hard to obtain, players are constantly running out of in-game currency. This is a common situation where the game companies are making real money. They create in-game shops that offer more currency for real money (like dollars). For example, in Genshin Impact, players can purchase Genesis Crystals with real dollars and then convert them to Primogems for the gacha.

The random reward system can make for exciting gacha games, but it can also complicate the experience since players spend time and or money trying to obtain the best characters or items.

This thesis will look at the math rules that make gacha systems work efficiently for companies. We'll see how ideas from probability (chances) and statistics (collecting and understanding numbers) are used carefully to make players want to play more and to help games

earn the most money. We'll focus on how gacha works in popular games, especially from HoYoverse, which is a major company in the mobile gacha business.

Game designers try to use exact math models and ways to count combinations to control how rare and easy to get virtual items are. This math control directly affects the probability of how items are given out in the game. This makes players want to keep spending money, which consequently leads to the large profit for the companies. Searching through the gacha with math, we want to show how gacha games produce a lot of money.

Gacha Systems: How They Work and Their Chances

As I said, the gacha system mostly makes money from mobile games. Players use in-game money to get a random prize from a set list of items. In games, these prizes can be many different virtual things, like characters you can play, strong weapons, special outfits, or important upgrade materials. The exciting feeling when players get through having a gacha affects them to try several times more.

What are the basic systems of Gacha(Fact)

Main Parts of Gacha Systems The chance-based nature of gacha has a few main parts:

- Banners/ Pools: Gacha games usually have different "banners" or "pools." These are special offers that might be for a limited time or always there. Each banner has a specific group of items with different chances of getting them. These pools are carefully set up to control how many virtual items are available and how much players want them.

- Base Drop Rates (Chances): Every item in a gacha pool has a "drop rate." This is the chance of getting that item in one try. These rates are usually shown in the game, but players often don't fully understand what they mean, especially when they try many times.

- Pity Systems (Guarantees): To help players not get too frustrated when they have bad luck for a long time, and to keep them playing, many gacha systems have "pity systems." A normal "hard pity" system promises that you will get a rare item after you try a certain number of times and don't get it. This means players will eventually get the rare item they want, which makes them want to keep spending until they get it.

- Soft Pity: Besides hard pity, some systems have "soft pity." This makes the chance of getting a rare item slowly go up as a player gets closer to the hard pity limit. This small change in chances makes the next tries feel much more valuable.

- Currencies: To use gacha, you need to spend in-game money. This money can be earned by playing the game (soft currency) or bought with real money (hard currency). How much

players think the money is worth and how hard it is to get soft currency often makes players use real money to buy hard currency for more tries.

Real money (won)	In-game currency (given + bonus)
1200	60
5900	300+30
19000	980+110
37000	1980+260
65000	3280+600
119000	6480+1600

The Math of Gacha

The profuse amounts of money that gacha systems make is a good illustration of how strong the foundation is in the math for gacha systems - probability (chances) and combinatorics (ways to combine things). These two math approaches are basic tools that a game creator can use to create a variable gacha system that is fun and generates large amounts of money. It is very important to understand these math ideas to know how gacha games actually generate money.

Basic Chances

What Happens in One Try At its most basic level, gacha works on simple chance rules. Each item in a gacha pool has a "drop rate," which tells you how likely it is to get that item in one try. This rate is usually a small percentage. For example, a super wanted S-Rank character in a popular gacha game might have a basic drop rate of 0.6% (or 0.006). Here's a simple way to think about chance:

$$\text{Chance of (Something Happening)} = \frac{(\text{Number of Good Outcomes})}{(\text{Total Number of Possible Outcomes})}$$

In a gacha system, if a rare item you want has a chance of r , then the Chance of (Desired Item) = r . It's important to remember that each try is separate. So, what happened before doesn't change what happens next, unless a pity system is active.

Total Chances: What Happens Over Many Tries Even though the chance of getting a rare item in one try is often low, players usually try many times. The total chance of getting an item you want goes up with more tries. But you can't just multiply the chance of one try by the number of tries. A better way is to figure out the chance of not getting the item and subtract that from 1.

Let P be the chance of success (getting the item you want) in one try. The chance of not getting the item after n tries is $(1 - P)^n$. So, the total chance of getting at least one item you want after n tries is:

$$\text{Chance of (at least one success in } n \text{ tries)} = 1 - (1 - P)^n$$

Example (S-Rank Character in a HoYoverse Game): Imagine an S-Rank character in a HoYoverse game with a basic drop rate $P = 0.006$. The chance of not getting this character in one try is $1 - 0.006 = 0.994$. If a player tries $n = 100$ times, the chance of not getting the character in all 100 tries is 0.994^{100} , which is about 0.548.

So, the total chance of getting the character at least once within 100 tries is $1 - 0.548 = 0.452$, or 45.2%. This shows that even with many tries, you're not guaranteed to get it, which quietly makes players want to keep trying.

Pity Systems and Average Value Pity systems completely change the chances in gacha. A "hard pity" system promises you'll get a rare item after a certain number of tries, let's call it K . This means there's a limit to how many tries a player has to do to get a guaranteed rare item. While this seems good for players, it also gives them a clear goal for spending. Players are encouraged to keep trying until they hit this pity limit, knowing their money will eventually get them the rare item they want.

The concept of "average value" (E) is really valuable when analyzing pity systems. Average value is what would happen on average if you performed something a large number of times. In gacha, it is used to estimate the average number of attempts (and cost) to obtain a particular item, given various drop rates and pity rules. For a system with a constant drop rate P and a hard pity at K attempts, the average number of attempts to obtain the item can be estimated as:

$$E = (\text{Expected number of pulls until success, including pity})$$

This is slightly harder to calculate precisely without advanced math, but the general principle is that pity systems render the average number of tries much more consistent and often shorter than if there were no pity whatsoever. Essentially, it's the average number of tries a player can expect to have to make in order to obtain their desired item, due to the guarantee.

How Soft Pity Changes Things Soft pity makes the chance of getting a rare item go up as a player gets closer to the hard pity limit. In many popular gacha games, like those from HoYoverse, the basic S-Rank drop rate is usually 0.6%. Soft pity often starts around 75 tries, with the chance going up a lot until the hard pity of 90 tries. While the exact soft pity curve can be tricky and different for each game, the main idea is that the chance of success goes up quickly in the tries leading up to the guaranteed pity.

For example, if the basic S-Rank chance is 0.6% for tries 1-74, it might go up to 6% for tries 75-89. This means that within the soft pity range, players are much more likely to get the

S-Rank character before hitting the hard pity limit. This smart increase in chance makes players feel like they should keep trying, because they think they have a better chance of getting what they want with each try in the soft pity window.

Combinations: Getting More Than One Item While chance tells us how likely it is to get single items, combinations become important when thinking about getting different sets or groups of items.

For example, if a player wants to get k unique items from a group of N items available, the number of different ways these can be combined is found using this formula:

$$C(N, k) = \frac{N!}{k! \times (N-k)!}$$

Here, “!” means a factorial. For example, $5!$ is $5 * 4 * 3 * 2 * 1 = 120$. This formula shows how many possible collections there are in a gacha system. This complex way of combining things affects how long players stay interested, as they try to complete specific sets of items for in-game benefits or just to collect them. Even though it's not directly about the money made from one gacha try, combinations help us understand how deep the game's collection system is and how it can keep players interested for a long time.

Making More Money with Math Design Game makers use the math rules of gacha systems in smart ways to earn more money. This involves a clever mix of game design, how new content is released, and smart use of chance models.

Free-to-Play Model and Making Money Gacha games mostly work on a free-to-play (F2P) model. This means anyone can start playing because there's no cost to begin. The main way they make money is by selling special in-game money, which is mostly used for gacha tries. This money-making structure is designed with math to make sure that a small group of very dedicated players, often called "whales," bring in a very large part of all the money. At the same time, a large group of free players helps make the game world lively and active.

The concept of "average value" (E) is really significant when considering pity systems. Average value is what is expected to occur on average if you New Content and Scarcity One of the main ways gacha games generate revenue is that they constantly introduce new, cool things, such as new characters or powerful weapons. They are generally available for a limited time in gacha banners. This generates a constant cycle of hype and demand. The game developers intentionally make things scarce by making them available for a limited time.

This employs the concept of urgency, with players wanting to try immediately before the offer expires.

This rapid launch of new material maintains the players' attention and encourages them to spend money constantly.

Smart Pity System Design for More Money Pity systems, even though they seem good for players, are actually very good tools for making more money. By giving players a safety net, they also create a clear and expected spending goal. Players know that a rare item is guaranteed after a certain number of tries, so they often decide to spend just enough to reach that pity limit,

even if they didn't plan to spend that much at first. The clever way soft pity is used, which slowly increases chances as players get closer to hard pity, makes this behavior even stronger by making players feel less worried about long periods of bad luck.

Power Creep and Always Spending Though games tend to be balanced, when new virtual goods are introduced, they usually create "power creep." This is when newer items are slightly better than the previous ones. New characters or weapons may have superior skills, be more compatible with current game mechanics, or have superior statistics. That makes them highly desirable for players who enjoy competition or who wish to conquer difficult sections of the game. This ongoing release of slightly more powerful content utilizes mathematics to encourage players to try out new banners, even if they already possess numerous items.

Conclusion

Gacha systems are not just entertainment; they are complex business models supported by deep mathematics. This paper has demonstrated that gacha games develop mathematics including probability and combinatorics to help keep players engaged and allow continued revenue. The strength of these systems is the ability to manipulate players psychologically while generating reliable financial returns.

The basis for gacha systems are based on 'probability'. Every time you obtain a specific item, the chance of obtaining that item can be represented by this formula:

$$\text{Chance of (something happening)} = \frac{\text{Number of good outcomes}}{\text{Total number of possible outcomes}}$$

This equation demonstrates that when an extremely rare character has a 0.6% acquisition rate, it represents the proportion of favorable outcomes among all possible attempts. The independence of each attempt is crucial - previous results do not influence subsequent tries, compelling players to continue attempting until they obtain their desired items. The probability of securing a desired item across multiple attempts differs significantly from single-attempt calculations. The likelihood of achieving at least one success in 'n' attempts follows this pattern:

$$\text{Chance of (at least one success in } n \text{ tries)} = 1 - (1 - P)^n$$

Where 'P' represents the success probability for a single attempt. For instance, when attempting to acquire an item with a 0.6% probability across 100 tries, the chance of complete failure is approximately 0.548. Consequently, the probability of obtaining the item at least once within 100 attempts equals 1 minus 0.548, yielding 0.452 or 45.2%. This demonstrates that even numerous attempts provide no absolute guarantee, motivating continued player engagement.

A further vital part of gacha systems involves combinations - when a player is trying to collect as many unique items as possible, combinations will be key. How this is calculated is

using combinations: when the number of ways to get 'k' unique items from 'N' different items is as follows:

$$C(N, k) = \frac{N!}{k! \times (N-k)!}$$

Here, '!' denotes factorial operations. This formula illustrates the various combinations required to complete specific item sets or collections within the game. This contributes to long-term player engagement and enhances the game's depth and replay value.

These Mathematical concepts interact with 'Pity Systems' to create maximum gacha profit. 'Hard Pity' guarantees eventually acquiring a rare item after making a pre-established number of attempts (K attempts). Hard Pity gives players clear target spending amounts to seek out a rare item. Players are able to spend K amount of dollars attempting to get a desired item. And while this appears to be better for players it is actually a clever system that forces players to spend until they 'achieve' their goal.

Not only that, but 'Soft Pity' increases the rare item drop rates leading up to the hard pity limit. For example, if the S-rank character has a 0.6% base drop rate for the S-monthly gacha, once players hit the 75th attempt they would have their drop rate increased to 6% on the gacha. This doesn't appear to be a major probability change, but this mental shift creates expectations with players that they are due for success, and encourages the players to spend further attempts before possibly being harshly pitied. This is a promising psychological mechanism that reduces player frustration and establishes continued spending.

Ultimately, gacha games come down to more than just luck. They construct business models based on rigid mathematics. Game developers rely on mathematical principles like probability, combinatorics, and pity systems to understand player behavior, incentivize player engagement, and see revenue grow. Players benefit from understanding these principles; not only does it help them play reasonably, but it also creates an understanding of the world of digital entertainment. Mathematical models will remain a mainstay in the mobile gaming vein, and gacha systems will continue to grow as their math evolves.

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A Study on the Language of Gender in Indian Advertisements By Navyaa Kochhar

Abstract

This research paper investigates how marketing strategies, especially in the form of advertisements, have evolved in India over time. By treating gender as the primary analytic lens here, this paper dissects how identitarian ideas of gender have been strategically deployed in advertisements to influence their spectator-customers. Advertising reveals itself as a mirror of social norms but by wielding great control over the commercial choices of its consumers, it has also become a means through which social norms are just as equally defined, making it a persuasive yardstick for social research, too. Through a combination of historical media analysis and consumer surveys, this research paper looks at how attitudes towards gender have evolved in advertisements and how the modern Indian consumer now responds to advertisements that either rely on conventional gender stereotypes or ones that are ostensibly gender progressive.

The findings reveal complicated responses to advertisements coded in the language of gender: even as audiences remain critical of them, stereotypes remain commercially functional and more often than not, a strategic marketing choice. While the female respondents of the consumer surveys viewed stereotypical advertisements with greater concern, the surveyed men were generally more accepting of them. The research paper identifies this as a social tendency of complacency, where groups relatively unaffected by a prevalent social narrative have little incentive or willingness to remedy it. Through these findings, this paper presents social change—anchored through media—as not a linear process but a constellation of competing political actions.

Keywords gender, media, culture, India, marketing

Introduction

Background

Advertising can be seen as a minute facsimile of how gender and social norms have evolved over time. Advertising is often perceived as a mirror of society, where it reflects contemporary and present-day norms. But more often than not, it plays an equally productive role, too, where it does not merely reproduce prominent social norms but also produces them. From television commercials in the 1970s to influencer-driven content in the 2020s, the portrayal of gender in advertising reveals more than just trends; it reflects shifting gender roles, cultural evolution, and strategic economic decision-making. From above-the-line marketing such as television, radio, and billboards to targeted social media and online marketing, they influence not only how certain genders are externally perceived but also how they behave. Advertising, by making similar social and gendered claims in different forms, equally facilitates a process of identitarian internalisation, where women and men are led to believe that they have rigid, unshakeable roles to play in society. Within catchy jingles and glamorous portrayals lie

undertones of cultural norms and biases that have been deeply embedded and accepted in society. Nowhere is this as stark as in the portrayals of roles and expectations for men and women in a manner that limits their individuality and reinforces certain gender stereotypes.

Problem Statement and Research Objective

This research paper aims to look at a few of the most common gender stereotypes that were propagated by advertisements since the 1970s until more recently and how marketing strategies have evolved over time and space. It investigates the economic, social, and cultural motivations behind gendered advertising, evaluating changes across decades. Using content analysis and consumer surveys, the study examines how gendered advertising persists, adapts, and influences consumer perception.

Hypothesis

This paper predicts that advertisements and the propagation of gender stereotypes do not have a straightforward correlation. It would be reductive to claim that advertisements only further social and gender norms that treat, both, women and men as singular, mutually exclusive social identities. Popular advertisements, it is hypothesised in this paper, have evolved over time, in the process breaking gender stereotypes and leaving powerful messages for wider change across society. There has been a paradigm shift as new advertisements recognise the need for gender equality, although they still express that ideal in relatively conservative terms since they cannot escape the language of social norms, even if they intend to move away from it. This paper also hypothesises that the surveyed respondents of this study may view the modern-day progressive advertisements more positively.

Significance of the Study

The field of gender studies has grown over time as research within the humanities finds a wider audience. Gender studies predominantly interrogates questions pertaining to identity formation, gender roles, perceptions, culture, and media. A lot of the media used to evaluate attitudes towards gender in society are narratives of fiction, such as films, television shows, books, and music. Advertising is usually perceived as a predominantly commercial enterprise, with its primary motive as that of profit-making. However, in treating advertisements as narrative texts, too—fiction or not—we can open avenues for further research into gender roles. It not only allows us to complicate how gender roles are propagated and produced but also allows us to view advertisements as texts of culture. By combining these two focus points, we can use media sociology as an instrument to effectively diagnose the state and evolution of gender. Moreover, this research is significant outside academia, too. It holds practical significance for marketers, policymakers, and companies concerned with inclusive advertising practices.

Scope and Limitations

The aforementioned consumer survey analysis focuses primarily on a few Indian advertisements and four different product categories. Since respondents do not have the bandwidth to evaluate a large number of advertisements, this study had to be strategic about its choice of brands. Moreover, the advertisements shown to respondents were either categorised as stereotypical or as progressive—a categorisation not visible to the respondents—to streamline the process of advertisement selection. However, this study is conscious of the fact that such binary framing risks oversimplifying the complicated politics of gender in media. Moreover, the survey sample size is modest due to the practical limitations of fieldwork research, leading to uneven distributions of gender and age that may influence patterns of responses.

Literature Review

In this section, the paper presents a summary and analysis of existing research on the role of advertising in producing and reproducing gender norms. It traces a chronological overview of advertisements, drawing on scholarly studies in the field to both demonstrate the validity of this research, and to identify the lacunae and fertile entry points within existing scholarship that justify the significance of this paper's contributions.

The advertising industry, as we know it today, can be traced to the invention of the printing press in the 15th century, which made mass-produced pamphlets more feasible, paving the way for the first paid advertisement in a newspaper in 1704 (“History of Marketing”, 2025). The industrial revolution of the 19th century, then, led to the emergence of the first modern advertising agencies, beginning with Volney Palmer in the U.S. in 1841. These agencies not only brokered media space but also crafted campaigns, marking a shift away from simple publicity to professionalised brand promotions (“History of Marketing”, 2025). It is within these crafted campaigns—and more pointedly, the gendered dimensions of these campaigns—that this research paper's thesis resides.

Advertising has consistently reflected shifts in gender roles, initially lagging behind social reality by just mirroring the domestic and professional realms of society. Globally, advertisements in the 1950s post-war era reinforced the domestic ideal: women as homemakers and men as breadwinners. In India, this was echoed in campaigns for detergents, soaps, and kitchen products, where women were portrayed as by-default caretakers (Das, 2024). Between the 1970s and 1980s, as women gradually entered the labour-market and workforce, female portrayal in advertisements evolved, too. Rather than treating women solely as domestic commodities, advertisements presented women in “dual roles”—professionals by day, homemakers by night—a framing that inadvertently reinforced the notion that domestic labour is a women's responsibility (Gupta, 2023). In 1990s India, during the liberalisation of its economy, this stereotype persisted. This time, advertisements took a “superwoman” angle, where women excelled in their professional lives while still solely managing domestic tasks (ASCI, 2022). Similar to advertisements in the prior two decades, women in media were treated as female role models to emulate, insofar as they also succeeded domestically. Across the fifty years, women's

domestic responsibilities in these advertisements remained untouchable and unalterable, while only their external lives were treated with dynamism.

It was with the momentum of the feminist movement in the 2000s, coupled with the rise of online globalisation that facilitated the global transfer of messages, that attitudes towards gender in advertising began to change. Rather than focus on a gender's household and professional responsibilities, advertisements used inclusivity and empowerment as selling points: men can take the domestic charge and women the professional. However, critics dismissed this shift as largely performative, terming this new media phenomenon as “commodity feminism” (a nod to the Marxist concept of commodity fetishism), where empowerment is marketed through a neoliberal, capitalistic economic system that actually attempts to subjugate (Gill, 2007). What advertisements, then, present is not an ideal of empowerment but a hollow image, where gender inclusivity is exploited for the sale of goods and services, especially beauty products, wellness drinks, and domestic appliances.

Gill (2007) argues that contemporary advertisements frequently commodify empowerment by selling a language of choice, confidence, and “real beauty”, while leaving underlying power relations intact. Brands often signal progressivism in tone yet fall back on conventional casting, settings, and narrative arcs. This reflects Goffman's (1979) claim about advertising not simply being an economic activity but a “culture industry”. Culture industry, in this case, refers to a system where agencies mediate between brands and media to promote goods and services, rooted in societal communication norms. Goffman (1979) argues that visual cues in ads reinforce existing socio-cultural norms and values, particularly around gender. In India, gendered advertising has drawn deeply from traditions: women framed as caregivers, and men as protectors and decision-makers (Sharma & Bumb, 2021). Additionally, Western colonisation, embedded in India's social landscape, is another force that has shaped Indian advertising. For instance, fairness creams like Fair & Lovely borrow from Western ideals of beauty that equalise lighter, fairer skin with beauty and opportunity (Livemint, 2017). Similarly, luxury product advertisements in India replicate Western tropes of women as glamorous objects of desire. Goffman (1979) argues that the aforementioned visual cues—size, touch, gaze, function ranking—not only reflect such social hierarchies but in turn, normalise them.

With the advent of feminism and globalisation that has facilitated the spread of feminist thinking, consumers are more attuned to socially-regressive branding and advertising. This has also helped lift the veil on companies posturing as inclusive and progressive through their advertisements, impelling such companies to also adjust to cultural pressure. Campaigns such as the 2022 Layer'r Shot deodorant advertisement were banned after public backlash for trivialising harassment, proving that advertising now exists in a feedback loop with social discourse (ASCI, 2022). However, despite this, as progressive casting in advertisements incrementally improves, recent global tracking confirms that stereotypical portrayals of gender continue to prevail even today. The Unstereotype Alliance's Unstereotype Metric (UM)—run with Kantar across ~3,500 ads in 56 countries—shows only modest improvements in progressive portrayals since 2019, though higher UM scores correlate with stronger persuasion and purchase intent.

Modern society is increasingly divided across platformed media such as YouTube, social media, streaming platforms, and cable television. This means that gender, understood in a contemporary setting, is coded according to the media the consumer accesses, the advertisements specifically targeted to them on said media, and through vernacular content. In culturally diverse markets like India, this implies a market split: urban and younger audiences are shown inclusive, norm-challenging advertisements whereas older and media-conservative consumers are presented with advertisements reinforcing familiar domestic tropes (Dasgupta, 2020). This also supports the earlier thesis of slow progressive casting and stereotypes. There still exists a large consumer-base that responds well to advertisements that stereotype gender. Industry evidence from India captures this cultural double-bind. The ASCI–Unstereotype Alliance–Kantar study (2023) found that while 48% of Indian consumers actively want more inclusive advertisements, the remaining 52% of the consumers are completely absent from mainstream creative.

Through this literature review, I have sought to explain the sociological advancement of advertisements in a chronological fashion. I have used relevant scholars that diagnosed this particular state of media to demonstrate that this is a field of great academic importance. While they have presented us with the theoretical tools to understand the social condition of advertising, it is upon this research paper to apply this more pointedly to the Indian context. The following section will identify a few of the important advertisements that this paper analytically focuses on, upon which the tools mentioned in this current section will be employed.

Media Analysis

As claimed earlier, this section will present an overview of relevant Indian advertisements that will eventually form the anchor of this research study. These advertisements are described here in order to familiarise the reader with the Indian context of media. This section is largely divided into three parts: first, it will look at portrayals of women in advertisements; then, how men are in contrast shown; and lastly, how contemporary advertisements have attempted to subvert prevalent gender stereotypes.

Stereotypical Attitudes Towards Women in Advertisements

Commercial advertisements in the 1980s and 1990s, such as those for detergent powders like Surf and Nirma, consistently portrayed women as responsible for household chores. For instance, Lalitaji, in the Surf campaign, was shown as a strong and assertive homemaker who convinced audiences that Surf was the right product to buy even if at a higher cost (“Indian ad for washing powder Nirma”, 2022). Similarly, Nirma advertisements had another homemaker, Deepikaji. Both advertisement campaigns claimed efficiency for women, that these detergents will ease the load of women's domestic tasks. In doing so, they continued to reinforce the gender stereotype that only a woman can be at the centre of a household.



Figure 1.0: Horlicks' 1960s Advertisement (Dasgupta, 2020)

Another persistent stereotype in Indian advertisements has been the depiction of women as the primary caregivers of the household. Advertisements for children's health drinks like Horlicks repeatedly emphasised that women were solely responsible for their children's nutrition and wellness (Dasgupta, 2020). However, this caregiving also extends to adults in the household. Women in the advertisements are expected to support all of their husbands' endeavours, too. As shown in Figure 1.0, Horlicks capitalised on this expectation by marketing its dairy products through advertisements that depicted women serving milk at their husbands' gatherings.



Figure 1.1: Dalda's Advertisement

Advertisements have also historically tied women to the kitchen, portraying them as the ones responsible for cooking and cleaning. The 1982 Prestige cooker advertisement with the tagline "*Jo biwi se kare pyar, woh Prestige se kaise kare inkaar*" ["no one who loves their wife can say no to Prestige"] equated a man's love for his wife to buying a kitchen appliance for them (Livemint, 2017). While it portrayed women as cooks, it simultaneously positioned men as decision-makers, especially in matters involving money. Similarly, as shown in Figure 1.1, a 1960s cooking oil advertisement entrenches further the idea of women as primary caregivers, depicting them as solely responsible for preparing food for their children. What also makes these

findings interesting is also the paucity of advertisements that directly address men. As most advertisements seek to sell household products, women are overwhelmingly treated as the anchor of domestic media marketing.

Stereotypical Attitudes Towards Men in Advertisements

Advertisements from the 1980s and 1990s frequently depicted men as drivers or motorcyclists, always partaking in sporty and adventurous activities. The Hero Honda campaign with the tagline “Fill it. Shut it. Forget it” targeted Indian men, encouraging them to move away from scooters to instead embrace motorcycles as a symbol of masculine independence and efficiency (Livemint, 2017). Thrill-seeking and risk-taking has also been central to male-focused advertising. Mountain Dew’s campaigns in the 2010s and 2020s, with the slogan “*Darr ke aage jeet hai*” [“Ahead of fear lies victory”], consistently showed men engaging in extreme sports and high-adrenaline adventures. These advertisements celebrated the idea of men overcoming fear with courage, reinforcing the stereotype that adventure and physical risk-taking are masculine domains (“Mountain Dew”, 2011).

Subverting Stereotypes in Advertisements

Recent 21st century advertisements have attempted to challenge long-standing gender roles in Indian advertising by presenting more inclusive and progressive portrayals of both men and women. A lot of this can be attributed to a more feminist-positive social landscape that rejects conventional gender stereotypes. In order to cater to more progressive audiences, brands and companies have had to modify their marketing strategies. One of the most prominent examples of this is the new Horlicks advertisement—a company that, as noted earlier, was notorious for stereotyping women as domestic commodities—featuring actor Taapsee Pannu (“Strong bones to #StandStrong everyday”) which promotes women’s health and self-care. Instead of reinforcing the idea that women must remain fit to serve their families, it stresses on the importance of a woman’s own well-being. This is one of the few Horlicks advertisements that allows its women to stand independent of a family.

Similarly, other domestic responsibilities attributed to women have also been redefined. The Badshah Masala advertisement shows a mother encouraging her son to enter the kitchen, directly challenging the stereotype that cooking is solely a woman’s responsibility. The Godrej Group’s campaign takes this further by asking men to pledge to learn cooking at home. Under this initiative, Godrej Microwave Ovens even published a “ManCan” Cookbook (Godrej).

Within the field of sports media, which is mainly dominated by male-centered narratives, Ashok Leyland’s partnership with the Mumbai Indians women’s cricket team is another example of this shift from gender stereotypes. Their advertisement, aligned with the team’s anthem, champions diversity and encourages women to actively pursue their aspirations, thereby breaking away from the notion of sports as a male bastion (Ashok Leyland, 2024).

In all three events highlighted in this section, the language of gender and responsibilities continues to remain consistent. Rather than dismantling the idea that gender is what dictates

behaviour and the domestic world, regardless of whether an advertisement is traditionally stereotypical or progressive by those standards, these advertisements nevertheless anchor their ideas around gender. It is within this logic of gender and media that this research paper sets its focus. Despite the shift in focus in newer advertisements that have adopted an ostensibly progressive outlook towards gender, it nevertheless necessitates some interaction with gender in order to communicate its message effectively. Therefore, one must remain cognisant of this when analysing media from a socio-cultural lens.

Methodology

To investigate the influence of gender stereotyping on the perceived effectiveness of advertisements, this study adopts a comparative survey-based design. The objective is to assess whether advertisements that reinforce gender stereotypes are rated as more effective and influential than those that present gender in a seemingly progressive manner.

First, four products were selected for their relevance to the Indian consumer market and their varied gender-targeting tendencies. Laundry detergent advertisements were chosen for their traditional association with homemaking, a task that is predominantly attributed to women in Indian society. Advertisements on motorbikes were selected due to their historical focus on male consumers and masculinity in branding. The marketing of chai, as a product, was chosen due to its cultural significance and its popularity as a widely consumed product with a broadly gender-neutral audience. Lastly, Airtel, a telecommunications service provider, was chosen for the aforementioned reason: a diverse consumer base.

For each product, two advertisements were selected: one stereotyping advertisement that imputes to a specific gender certain roles and responsibilities and one gender-progressive advertisement that either remains gender-neutral in its outlook or one that deliberately reverses traditional gender roles. To ensure objectivity in this selection, advertisements were evaluated based on predefined dimensions and markers of gender stereotyping, as established in the previous section. Both advertisements within each industry were matched closely in format, duration, production quality, and thematic appeal in order to minimise the influence of extraneous variables on participant ratings.

The survey was conducted with 143 participants, all employed Indians between the ages of 18 and 60, consisting of 75 men and 68 women.

For the survey design, two distinct but structurally identical surveys were created: Survey A, which contained only the gender-stereotyping advertisements and Survey B, which contained only the gender-progressive advertisements. In each survey, participants were asked to rate each advertisement on a five-point Likert scale, where 1 indicates “least effective” and 5 indicates “most effective”. Participants were also asked a series of qualitative post-test questions that explored their underlying attitudes toward gender stereotypes within advertisements.

To control bias and maintain the validity of the results, each respondent viewed only one type of advertisement (either a stereotyping one or progressive). This reduced the risk of response bias that might occur if participants consciously identified the study’s underlying

purpose. The surveys were distributed randomly using nimblelinks.com, which generates a single hyperlink that evenly and blindly allocates respondents between the two versions.

Results and Discussion

The survey revealed clear differences in how respondents evaluated stereotypical advertisements against seemingly progressive ones. The progressive advertisements produced a more normal distribution of ratings, with responses clustered around the middle of the 1 to 5 scale. This suggests that audiences reacted to them in a relatively balanced way, with some finding them effective and others not, depending largely on the product. In contrast, the gendered advertisements experienced a more divisive distribution at-large. Responses were spread more evenly across the scale and often skewed leftward towards lower effectiveness ratings. Although the shape of the distributions remained broadly consistent across products, the stereotyping advertisements were consistently more polarising and likelier to draw negative responses.

When responses were disaggregated by gender, further patterns emerged. Men's responses followed similar patterns for both progressive and stereotypical advertisements, with only minor differences in preference. On average, however, they showed a slight inclination toward the stereotyping advertisements, rating them as more effective overall. Women's responses, however, diverged more. For the progressive advertisements, their ratings resembled the normal distribution seen in the general sample. In the gendered condition, however, their responses spread more evenly across the scale and leaned more heavily towards negative ratings. In some cases, women's reactions were sharply polarising, with strong ratings at both ends of the scale, suggesting heightened sensitivity to the use of gender stereotypes.

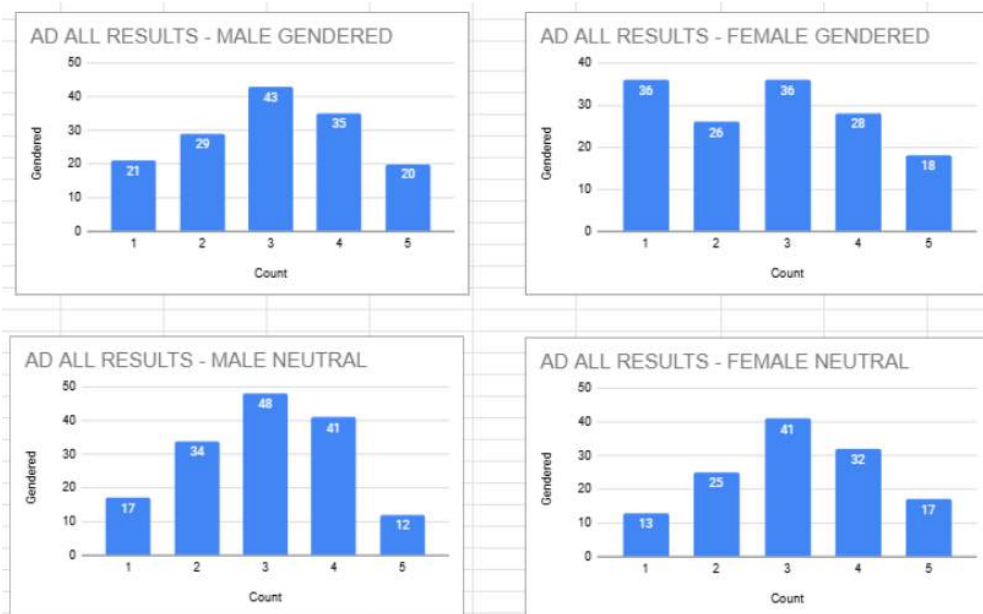


Figure 2.0: Distribution of Responses to the Advertisements

The results in Figure 2.0 show different patterns for men and women when comparing gendered and progressive advertisements. For men, the mean score for gendered advertisements was 3.03 (SD = 1.25) compared to 2.82 (SD = 1.12) for the progressive ones. The chi-square test gave a p-value of 0.476, which is much higher than 0.05, so the difference is not very statistically significant. This means that while men rated gendered advertisements a little higher on average, the difference could easily be due to chance, and overall their responses to both types of ads were very similar. For women respondents, the findings are quite different. Gendered advertisements had a mean of 2.76 (SD = 1.35) while progressive advertisements were higher at 3.12 (SD = 1.17). The chi-square test gave a p-value of 0.018, which is below 0.05, showing a statistically significant difference. This means women really did react differently, rating gendered advertisements more negatively than progressive ones.

The chi-square test is important because it evaluates whether the distributions of responses are meaningfully different. For men, the high p-value indicates no real difference between the two types of advertisements but for women, the low p-value confirms that the difference is real and not random. This supports what is already seen in the histograms in Figure 2.0: men's ratings looked similar across both types, while women's ratings of gendered advertisements were more spread out and often skewed negatively. Overall, this suggests that gendered advertising doesn't affect men much, but women are clearly less positive about it compared to progressive advertisements.

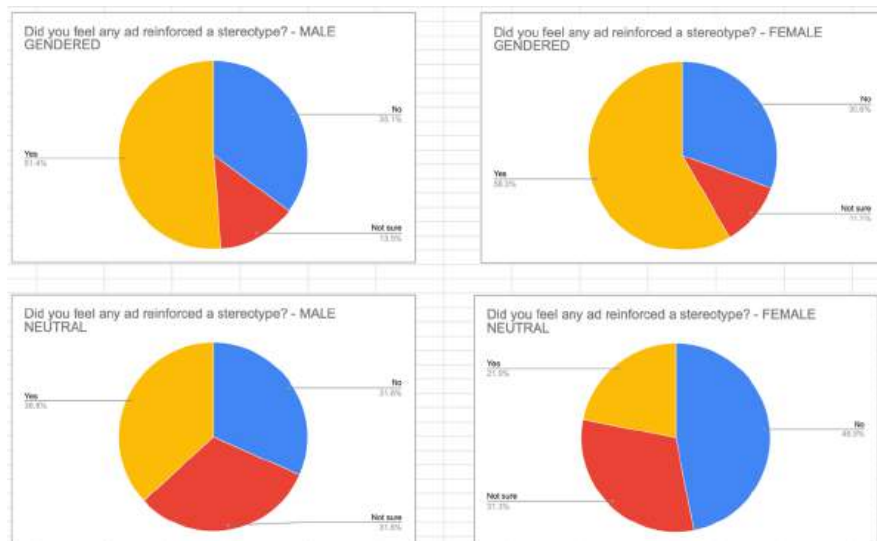


Figure 2.1: Charts on Stereotype Recognition

As Figure 2.1 shows, recognition of stereotypes was also markedly higher in the gendered condition. Amongst participants shown gendered advertisements, 54.8% identified stereotypes, compared to 32.9% who reported none. In their written responses, most participants described women as being portrayed as “housewives”, while others pointed to stereotypes of men as “macho” or “dominant”. A smaller group also observed women as “lovesick” in

advertisements. Differences in responses between the surveyed men and women were again visible here: women were 7% likelier than men to perceive stereotyping in the gendered ads (58.3% vs. 51.4%). In the survey about progressive advertisements, women were less likely to see stereotypes, with only 21.9% identifying them compared to 36.8% of men. This suggests women were more discerning in distinguishing genuine stereotyping, while men were more prone to perceiving stereotypes even where none were present.



Figure 2.2: Appropriateness of gendered advertisements, responses by men (left) versus women (right)

Judgments of effectiveness and appropriateness provided further insight. In the gendered survey, 51.4% of women rated the advertisements as effective compared to 40.5% of men, though women were also likely to rate them as ineffective. This was partly due to fewer women selecting “not sure”, which concentrated their responses at both ends of the scale. In the progressive advertisements survey, a larger percentage of men found these advertisements effective (44.7% vs. 36.8%), though rates of ineffectiveness were similar across genders. Perceptions of appropriateness, however, showed stronger divides. As shown in Figure 2.2, in the gendered survey, 72.2% of women judged the advertisements as inappropriate compared to 51.4% of men. Only 5.6% of women (two respondents) considered them appropriate, in contrast to 27% of men. In the progressive advertisements survey, women again leaned more critical, with 56.3% rating the advertisements as inappropriate compared to 42.1% of men. Although the gap narrowed for progressive advertisements, women remained consistently likelier than men to regard these advertising tactics as inappropriate.

Overall, 61 out of 143 participants were able to identify stereotypes, while 51 insisted that there were none, with the remainder uncertain. Those who recognised stereotypes were substantially more likely to judge the advertisements as inappropriate compared to those who did not. Yet despite this, both men and women frequently acknowledged stereotyping advertisements as effective even when they simultaneously rejected them as inappropriate. This disconnect suggests that respondents may believe such advertising strategically works on others while criticising it themselves. Men in particular may assume that stereotyped messages resonate with women, while women themselves often dislike the portrayals yet still concede their potential efficaciousness in shaping consumer behaviour.

The fact that stereotyping advertisements produced polarising responses, while progressive advertisements yielded more balanced evaluations, shows us that gender stereotypes

in advertising remain socially contentious and perceptions towards the same remain just as socially ambiguous. This aforementioned division between the effectiveness and appropriateness of an advertisement is an important point to highlight. While many respondents, most of which were women, regarded gendered advertisements as inappropriate, they acknowledged that other spectators may be successfully influenced by them. What this dissonance highlights is the commercial functionality of stereotypes, going back to an earlier point about the culture industry. Cultural and social ideas are not only reflected in the media but cleverly exploited in order to turn them into commercial profit centres. Just as the culture industry is a product of its surrounding culture, this external culture similarly evolves alongside the culture industry. This also encapsulates the dissonance between effectiveness and appropriateness here. While spectators of advertisements may be cognisant of harmful gender stereotypes, they are aware that their critique of it cannot change the larger culture that simultaneously produces such advertisements and equally, the larger culture that is produced by such advertisements. Advertising not only reflects but reinforces social norms, even when audiences consciously reject them.

These results reveal how advertising reflects and reproduces cultural assumptions about gender. Women's engagement with stereotyping advertisements suggests a broader cultural shift in how representation is perceived and what one may expect of it. By being more critical of female stereotypes in advertisements, we can see that women with progressive beliefs are also responsible for the progressive change in media messaging. On the other hand, men's relative acceptance of stereotypes in advertisements indicates that entrenched norms about masculinity and femininity continue to thrive amongst certain demographics. As a result, we see how social change is not only complicated but at a given time, extremely uneven, too. While feminist thinking has led to women's resistance to media stereotypes, men may not yet experience similar pressures to interrogate and dismantle conservative and traditional representations of either gender.

Men's general comfort with stereotypical portrayals of gender suggests that these images sustain a cultural framework aligned with their interests. The "macho" or decision-making roles ascribed to men in advertisements validate existing gender hierarchies, allowing them to read such portrayals as normal rather than problematic. For women, however, the repetition of stereotypes such as the housewife, as lovesick, or the self-sacrificing caregiver is experienced not only as inaccurate but as a cultural burden, which then becomes the driving force of their criticisms of such advertisements.

This unfortunate dynamic then reflects how advertising operates within the language of culture. Even when women identify gendered advertisements as inappropriate, they still admit that such campaigns work for others. This might show us that advertising's influence extends to collective social perception. A woman may dislike being portrayed as an unquestionable domestic figure but she still believes that others are persuaded by that portrayal. This recognition demonstrates how firmly rooted gender stereotypes are in the public consciousness. They do not

only function as instruments of marketing but also as cultural codes that audiences assume will resonate with others even if they disagree with these codes personally.

Conclusion

This research paper sheds light on how Indian advertising, for long now, has often relied on the language of gender for greater marketability. Even as modern day campaigns seek to forward a progressive message, they still rely heavily on a social and gender-dependent calculus. The section on media analysis demonstrates that a majority of advertisements—especially those trying to sell household products—relied on gender stereotypes. Women were treated as homemakers whereas men were the decision-makers. Over time, as feminist ways of thinking took greater global hold, advertisements attempted to flip the narrative by reversing these gender roles, still nevertheless relying on similar socio-cultural rhythms to build up their brand. The surveys of this research revealed that women, in general, were more critical of stereotyping advertisements than men, showing us that social strata that are not directly affected by certain essentialising beliefs have a weaker impetus to challenge the status quo. However, both men and women admitted that while they may agree or disagree with the message, they cannot dispute the fact that these advertisements are effective for a large portion of society. What this demonstrates is the culturally expedient nature of advertising: whether brands relied on stereotypical messaging or adopted progressive appeals, they did so because it promised sales, not because sociopolitical commitments of these companies evolved. Advertising, here, presents an important intellectual avenue into India's cultural imagination, both socially and commercially.

This study opens up space for greater research into how advertisements use the social world around it to convincingly sell a product. While this paper was particularly anchored around the dimension of gender, this research will hopefully be useful in providing data for more intersectional studies that look at identity formation in media and advertising through questions of class, caste, and sexuality, too. Given how culturally heterogeneous India is, media sociology will always be in want of further research.

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Correlation of Caffeine and Short-Term Memory in Teenage Girls

By Anam Zia and Noor-ul-Eman

Key Words

Short-term memory, Teenage girls, Adolescents, Cognitive.

Abstract

Caffeine is a naturally occurring psychoactive stimulant commonly present in everyday beverages consumed by teenagers. Previous studies have shown that optimum caffeine intake can enhance attention span and alertness, but its impact on short-term memory remains uncertain. This paper explores the correlation between caffeine and short-term memory in growing teenage girls by analysing data collected through surveys and conducting cognitive tests. Results indicated that caffeine offered a slight improvement in processing speed but had limited effects on memory span and accuracy. The impact of caffeine varied depending on caffeine habits, with regular and occasional caffeine consumers showing the most measurable results.

Introduction

For most teenagers, caffeine is not just an ingredient in a drink; it has become an integral part of their everyday ritual. (1) Chemically, a methylxanthine alkaloid with molecular formula $C_8H_{10}N_4O_2$, caffeine acts as a central nervous system stimulant by primarily acting as a non-selective antagonist of adenosine, A_1 and A_2A receptors. (2). This leads to increased levels of alertness (3) and reduced fatigue. Caffeine blocks adenosine, a substance that promotes fatigue and tiredness. In contrast, caffeine stimulates the release of neurotransmitters such as dopamine and norepinephrine, leading to increased neural activity, heightened arousal, improved vigilance, and enhanced cognitive function in specific aspects. (4) This renders caffeine a plausible neuromodulator candidate for short-term memory (STM).

However, the research on caffeine's impact on STM, particularly in teenage girls, remains unclear and inconclusive since their brains are still in the process of development and growth.

To understand the correlation between caffeine and STM, it is essential to define the terms first. STM refers to a temporary storage place that holds a small amount of information for a brief period of time (typically for a few seconds). It is described as a momentary workplace and plays a significant role in cognitive tasks. STM enables one to process information, allowing higher-level mental functions.

George Armitage Miller (1956) suggested that the capacity of STM is limited to about 7 ± 2 units, meaning that most individuals can only hold five to nine items at a time. He further explained that this limitation can be managed by organising information into larger, meaningful chunks, which allows people to process and recall more efficiently. (5)

Teenagers heavily rely on STM for their academics, whether for classroom learning or for exam preparation, so any systematic influence of caffeine on STM is worthy of research and

investigation, as it can have a meaningful impact on teenagers' academic and overall cognitive performance.

According to previous findings, STM is sensitive to various factors, including sleep quality (6), time of day (7), and individuals' differing levels of sensitivity to caffeine. (8) This makes investigating the effect of caffeine on STM alone difficult and more complex.

Prevalence and sources of caffeine in adolescents

Caffeine exposure in adolescents is worldwide and widespread. Parent-reported studies and large-scale surveys show that most, if not all, teenagers consume caffeinated beverages at least occasionally. According to the US National Dietary Surveys, 70%-75% of teenagers consumed caffeine on any given day. Parent surveys have further reported that soda is the most consumed caffeinated beverage, followed by tea, coffee, and energy drinks. According to reported literature, peer pressure and social media influence have played a pivotal role in promoting a caffeine culture by trending various types of coffee and energy drinks, making caffeine an integral part of teenage culture. (9)

In response to increasing caffeine consumption, public health bodies and paediatricians have issued guidelines. They have suggested that children under 12 should altogether avoid caffeine (10), while adolescents (12-18) should minimise their intake to the commonly cited threshold of 100mg/day (11). These guidelines were created to reflect concerns such as sleep disruption, cardiovascular problems, and changes in behavioural patterns, all of which directly affect overall memory performance.

Empirical findings

Previous studies have found that caffeine consumption influences many cognitive functions, including alertness, reaction time, logical reasoning and vigilance. (12,13) However, there are still inconclusive and inconsistent results between caffeine and advanced cognitive functions such as STM. (14) Some studies have been conducted to investigate the effect of caffeine on STM, but the studies concentrated on adults rather than adolescents. So the correlation of caffeine and STM, particularly in teenage girls, remains uncertain.

According to previous studies conducted with adults, caffeine shows a mixed impact on STM. Some studies have reported positive effects of caffeine, such as Borota et al. (2014) (Nature Neuroscience), which concluded that caffeine is a memory booster, enabling caffeine consumers to recognise learned images within 24 hours. (15) Similarly another study, McLellan et al., 2016 found that caffeine doses ranging from 40-300 mg improved both alertness and working memory accuracy in adult under normal and fatigued condition (16) Other research has proved that caffeine to negatively affect STM: an example of such research would be Sönmez et al. (2021), which demonstrated that high caffeine intake (>400 mg/day) resulted in poor sleep quality, indirectly harming STM. It also showed that overconsumption of caffeine can cause anxiety, jitteriness and impaired concentration, all of which can potentially reduce STM performance. (17) These mixed findings in adults underscore the need to investigate caffeine's effect on the STM in teenage girls.

Hypothesis

Caffeine consumption is hypothesised to influence short-term memory in teenage girls, with the effect varying according to individual consumption habits. Specifically, habitual consumers are expected to exhibit no significant change in memory performance, moderate consumers are expected to show a decline, and occasional consumers are expected to demonstrate an improvement in short-term memory performance.

Methodology

Study design

This study was carried out as a cross-sectional study with a crossover design, where the same participants were tested under both conditions once without caffeine and once after consuming a controlled caffeine dose. By using this approach, every student acted as their own control. This design was chosen to minimise the natural differences in cognitive ability from one person to another and to ensure that any observed difference would be due to caffeine rather than individual variation.

Participants

The participants were high school teenage girls aged between 16 and 18. The participants and their guardians were informed about the nature of the research and were asked to submit written consent. All participants participated voluntarily and were allowed to leave at any point in the study without facing any sort of penalty. All participants were asked to abstain from drinking any caffeinated beverage 24 hours before the experiment was conducted.

Materials

1. Surveys

Before conducting the memory test, participants completed an online survey to cover the baseline information. The Survey was conducted via Google Forms electronically, and all questions were MCQ for the ease of participants.

The survey consisted of the following question:

1. Do you drink any beverage with caffeine in it? (Yes/No)
2. If yes, what kinds of caffeinated beverages do you usually consume? (Tea, Coffee, Soda, Energy drinks)
3. How frequently do you consume caffeinated drinks? (Every day, Several times a week, Rarely, Never)
4. When do you typically consume caffeine? (Morning, Afternoon, Evening)
5. Do you think caffeine improves your ability to concentrate in class? (Yes, No, Maybe)
6. Do you believe that caffeine has an impact on your short-term memory, such as for tests, quizzes, or fact recall? (Yes, No, Maybe)

2. Test 1

Participants were required to complete Test 1, a computerised memory card matching test on Puzzle Org. The test consisted of a grid of concealed cards displaying words. Participants were then instructed to uncover pairs of matching cards with the same word. Each word would

stay revealed for 1-2 seconds, forcing participants to rely on STM. This task was given to investigate the effect of caffeine on STM processing speed and revival. The primary measurable outcome was completion time. Faster completion time indicated better STM performance, while slower completion time indicated impairment in STM.

Two variants were designed for Test 1: Test 1.1 and Test 1.2. Test 1.1 was assigned on day one, and Test 1.2 was assigned on day two to participants.. This was done to minimise the practise effect and increase accuracy.

3. Test 2

Test 2 was a standardized online test in which participants were tasked to observe the sequence of the square lighting up on a screen and then reproduce the same sequence later. The maximum sequence length was correctly recalled, meaning the highest level attained was the primary measurable outcome. This test was administered twice, once after Test 1.1 on day one and once after Test 1.2 on day 2. This task was given to investigate the effect of caffeine on STM performance, accuracy and capacity. Higher levels indicated an improvement, while lower levels indicated an impairment in STM.

Procedure

The first step was to obtain written consent from parents before proceeding with the study. Electronic surveys were then distributed after obtaining permission from the willing participants to collect their caffeine intake data and baseline information. All Participants were asked to abstain from consuming any caffeinated beverages 24 hours before the memory test was conducted.

Participants were randomly divided into two groups:

Group A, which received caffeine and Group B (control group), which did not consume any caffeine, on day one. Both groups maintained anonymity and were tested under identical conditions. They were both tasked to complete Test 1.1 and Test 2. Their Results were recorded. After 24 hours, on day two, the groups switched conditions. Group 2 was administered caffeine, while Group A acted as a control group. They were both tasked with Test 1.2 and Test 2. Their performance and scores from both tests were recorded and analysed, and the results were compared with survey data to assess the relation between caffeine and STM. All responses and data were ensured to remain anonymous and were stored securely for research purposes.

Data Collection and Analysis

Completion times from Test 1 and the highest level attained from Test 2 were recorded separately for each participant in controlled and standardised conditions. Survey responses were used to categorise participants according to caffeine consumption habits and to examine self-reported perceptions of caffeine's impact on attention and STM. Comparison between baseline and post-caffeine memory performance was conducted to assess potential correlations between caffeine intake and STM.

Precautions

This study was designed to be stress-free and brief for participants, making sure that the instructions are clear and straightforward. The purpose and results of the study will be shared with participants afterwards. The cognitive test was designed to be age-appropriate and to minimise the time required. Information on participants' caffeine intake was collected, and under experimental conditions, they were asked to consume a beverage containing 80 mg of caffeine, which falls within the moderate range of caffeine daily consumption for adolescents. (16) This was only done after receiving parents' and participants' consent. All responses and data were stored securely for research purposes only. Furthermore, participants were promised complete anonymity.

Results

Survey results

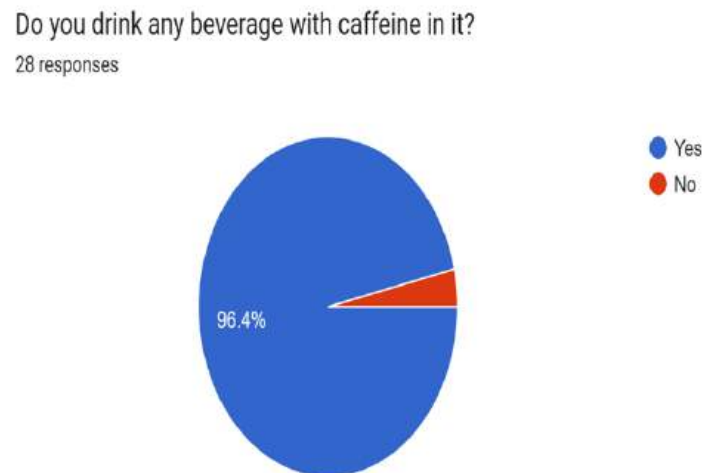


Figure 1.1: Survey result

If yes, what kinds of caffeinated beverage do you usually consume?

28 responses

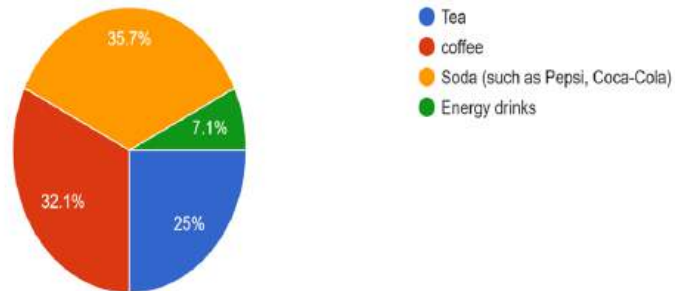


Figure 1.2: Survey result

When do you typically consume caffeine?

28 responses

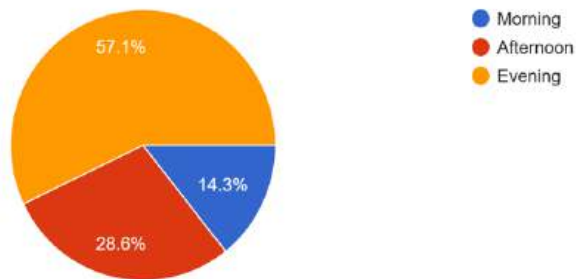


Figure 1.3: Survey result

How frequently do you consume caffeinated drinks?

28 responses

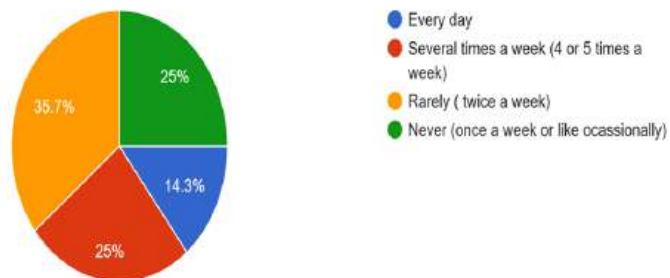


Figure 1.4: Survey result

Do you think caffeine improves your ability to concentrate in class? (do you feel more attentive or alert)

28 responses

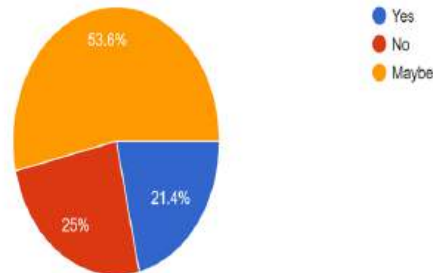


Figure 1.5: Survey result

Do you believe that caffeine has an impact on your short-term memory, such as for tests, quizzes, or fact recall?

28 responses

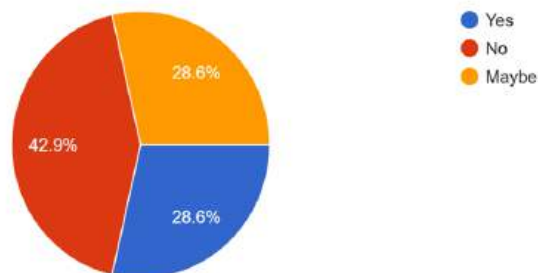


Figure 1.6: Survey result

Survey analysis

Twenty-eight participants took part in the survey, which allowed us to gain a clearer understanding of how often students drink caffeinated beverages and what effects they perceive. Out of 28 participants, about 96% reported drinking caffeinated beverages at least occasionally. When asked how often they consume caffeinated beverages, 14.3% claimed to consume caffeine daily, while one-fourth reported drinking it several times a week, and another one-fourth stated they never or only occasionally had caffeine. The majority (35%) reported consuming caffeine

rarely, almost twice a week. Soda turned out to be the most popular caffeine choice, followed by coffee. A smaller number preferred tea, and only a few admitted to drinking energy drinks.

Most of the participants consumed caffeine in the evening, while some preferred it in the afternoon, and only a handful took it in the morning at the start of their day. Their opinions about caffeine were interesting. The majority of them were unsure about how it affected them. 25% of them claimed that caffeine did not make them feel more alert and active, and did not play a particular role in helping them academically. 49.4% said they do not recall caffeine having an impact on their STM. Only 28.5% believed caffeine had a positive effect on their memory and played a role in their academic performance.

Experiment results

Group A				
Participant	Test 1.1 (with caffeine)/seconds	Test 1.2 (without caffeine)/seconds	Test 2(with caffeine)/level	Test 2(without caffeine)/level
PA1	74.88	107.35	9	7
PA2	53.24	61.00	9	12
PA3	61.10	93.30	8	8
PA4	106.10	140.06	8	8
PA5	82.92	52.04	10	11
PA6	80.33	86.43	9	7
PA7	45.00	49.48	14	11
PA8	75.36	42.00	11	12
PA9	57.05	74.05	9	10
PA10	89.08	76.07	9	8
PA11	67.88	68.00	8	9
PA12	47.81	52.60	9	8
Average	70.06	75.20	9.416666667	9.25

Group B

Participants	Test 1.2 (with caffeine)/seconds	Test 1.1 (without caffeine)/seconds	Test 2(with caffeine)/level	Test 2(without caffeine)/level
PB1	50.00	74.00	11	12
PB2	76.00	69.49	10	10
PB3	45.62	49.68	12	11
PB4	65.99	66.00	9	9
PB5	92.66	150.09	7	9
PB6	65.32	70.15	9	9
PB7	56.33	73.21	9	7
PB8	75.40	74.45	8	9
PB9	55.00	58.92	9	9
PB10	44.78	63.96	12	10
PB11	53.60	52.03	9	9
PB12	185.77	75.45	7	8
Average	72.21	73.12	9.333333333	9.333333333

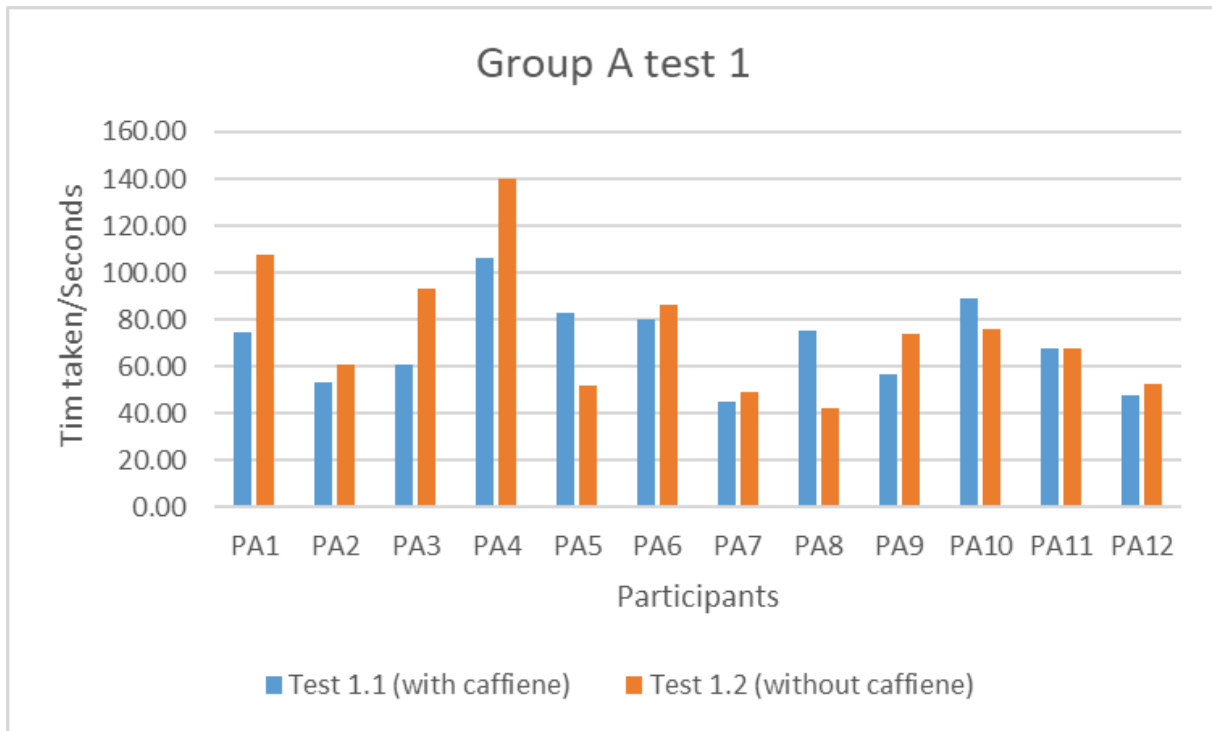
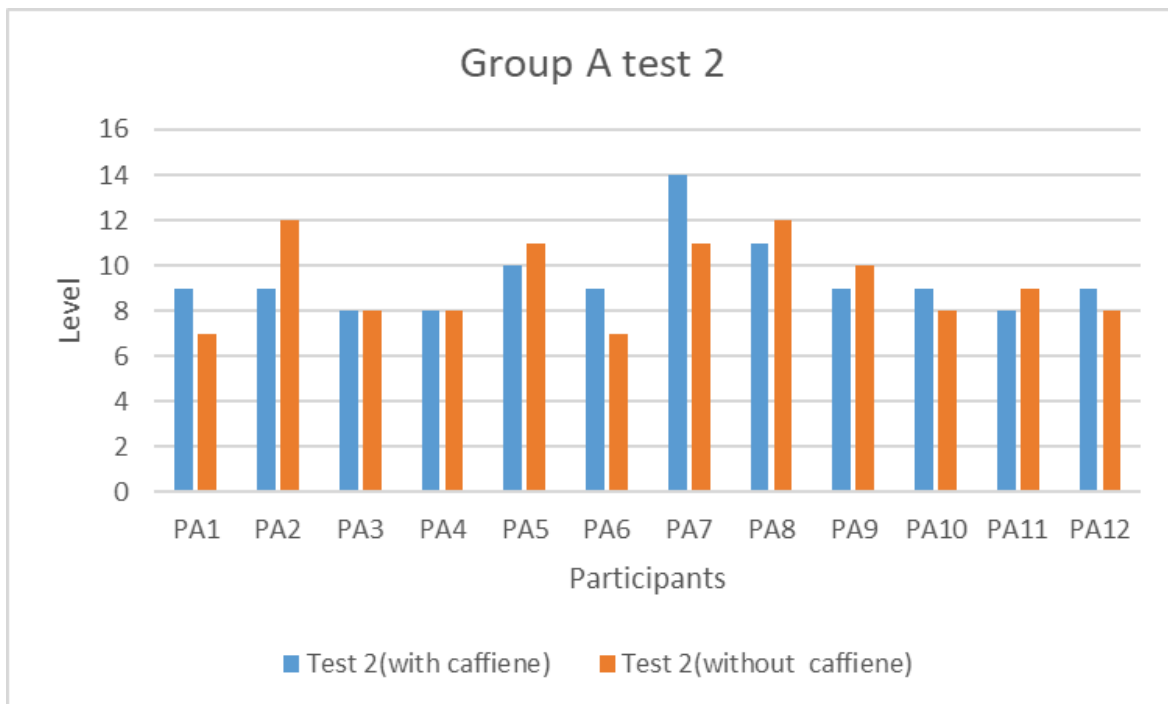


Figure 2.1: Comparison of short-term memory test 1 results between participants with and without caffeine intake (Group A).

Figure 2.2: Comparison of short-term memory test 1 results between participants with and without caffeine intake (Group B).



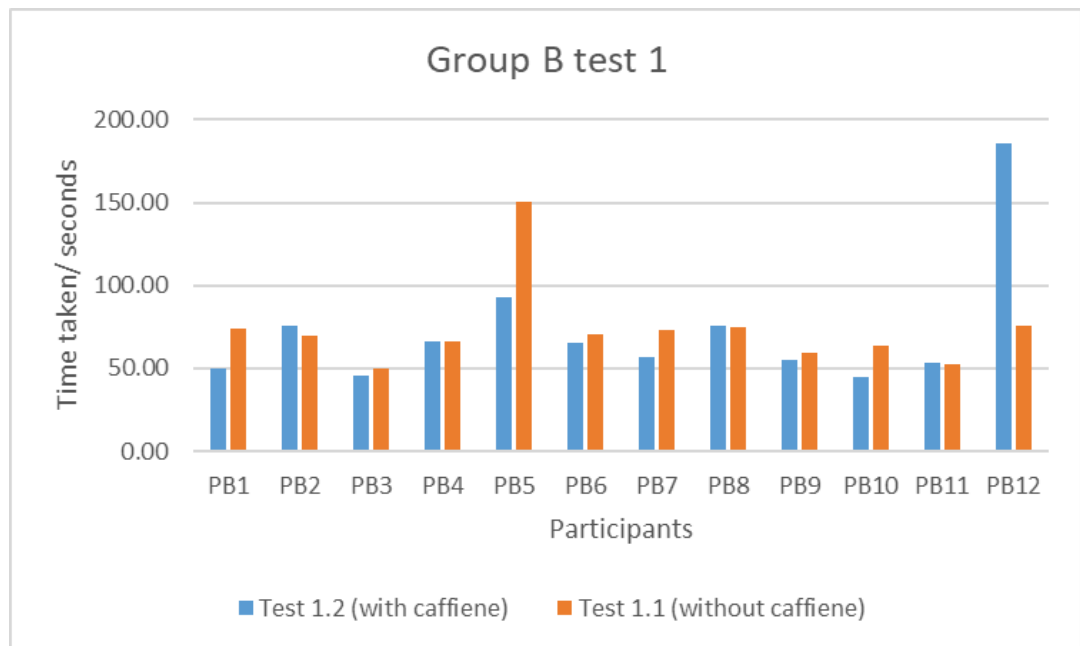


Figure 3.1: Comparison of short-term memory test 2 results between participants with and without caffeine intake (Group A).

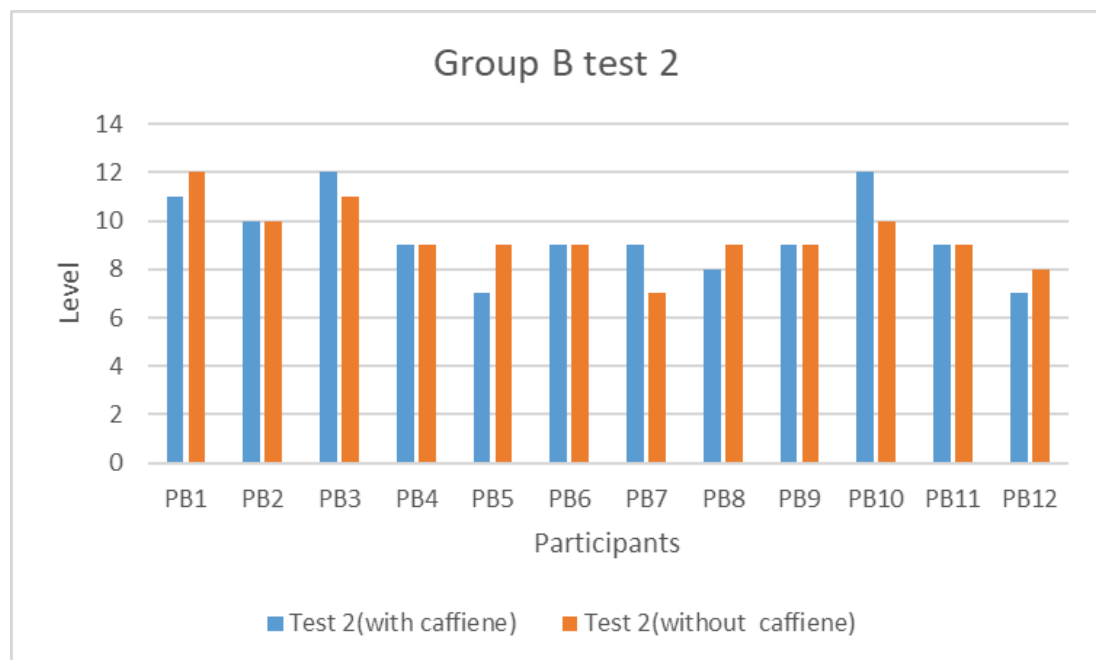


Figure 3.2: Comparison of short-term memory test 2 results between participants with and without caffeine intake (Group B).

Experiment analysis

Twenty-four participants volunteered to participate in the experiment. The participants were randomly divided into two groups. Each group's participant completed task 1 and task 2 with and without caffeine, with a 24-hour interval.

Group A (caffeine → no caffeine): Group A average completion time for Test 1 was 70.06 seconds with caffeine and 75.20 seconds without caffeine. Their average highest level attained on Test 2 was 9.42 with caffeine and 9.25 without caffeine.

Group B (no caffeine → caffeine) Group B average completion time for Test 1 was 72.21 seconds with caffeine and 73.12 seconds without caffeine. In contrast, the average highest level attained was identical under both conditions (9.33).

In group A, caffeine overall showed a positive effect. It improved both completion time and the highest level attained slightly. However, in contrast, group B showed a minor improvement in completion time, but none in the highest level attained.

The results suggest that caffeine may offer a small yet measurable improvement in STM. Group A, which was administered caffeine first, showed a visible and consistent trend of faster completion time and marginally higher level scores. However, group B did not demonstrate a notable trend. Group B demonstrated a slight improvement in completion time, but no significant change in level.

Experiment discussion

The findings of this study are consistent with earlier studies that have proved caffeine to enhance alertness and cognitive processing speed, such as McLellan et al.2016. However, the slight difference found between caffeine and non-caffeine conditions suggests that caffeine's impact on STM in female teenagers is subtle. This may be because their brains are still in different and crucial stages of development, undergoing growth. (20)

In line with this, caffeine appeared to be more beneficial for speed-based tasks (Test 1) than for accuracy or the expansion of STM span (Test 2). This implies that caffeine may boost attentional focus and response speed but not necessarily expand memory capacity or improve accuracy.

The variation in group A and B results may highlight the carryover effects or differences in individual sensitivity to caffeine. Teenagers who regularly consume caffeine may have already developed a tolerance to it, reducing its measurable impact. The difference in result also suggests that while caffeine may sharpen focus and slightly enhance STM performance, its effects are neither uniform nor consistent and may vary depending on prior consumption habits, caffeine sensitivity, baseline tolerance or cognitive test type. Additionally, factors such as sleep quality, time of day, and natural differences in learning ability may have influenced the outcome.

After collecting data from the survey and experiment, participants were divided into four categories based on their frequency of caffeine consumption. This was done to investigate if caffeine's impact on STM is related to the frequency of caffeine consumption. The following are the results:

Type of consumer	Average time taken without caffeine/ seconds	Average time taken with caffeine/seconds	Percentage change in average time taken	Average level without caffeine	Average level with caffeine	Percentage change in level
Everyday	85.005	69.76	18%	9.5	9.5	0%
Several times a week (4 or 5)	78.76	91.35	-16%	8.66666667	8.83333333	2%
Rarely (twice a week)	66.17	61.17	8%	9.625	9.25	-4%
Never (once a week or like occasionally)	72.97833333	70.98	3%	9.33333333	10	7%

Analysis

Every day, consumers took 85.005 seconds on average without caffeine and 69.6 seconds with caffeine. They improved by 18% in test one. Their level, however, remained unchanged. Several times a week, consumers showed a decrease of 16%. Their average time taken increased from 78.76 seconds to 91.35 seconds. However, interestingly, their level improved by 2%. The time for rare consumers of caffeine dropped from 66.17 seconds to 61.17 seconds. They showed an 8% improvement. However, their level dropped by 4%. Participants who rarely consumed caffeine experienced an average improvement of 3% in the time taken and 7% in the level.

Discussion

The results of this study show that caffeine does not affect every individual in the same manner. The impact of caffeine on STM differs according to how frequently one consumes caffeinated beverages. Participants who consumed caffeine regularly showed a substantial improvement in speed; their completion time showed the greatest improvement, although their

level remained unchanged. This suggests that consuming caffeine regularly may enhance recall speed, but it does not increase memory span or accuracy. According to previous research, since habitual consumers consume caffeine regularly, they often develop tolerance where caffeine primarily helps restore alertness rather than providing new cognitive benefits. This allows frequent caffeine consumers to process information more quickly. (21)

On the other hand, Participants who consumed caffeine several times a week showed a very different and interesting outcome. Their completion time slowed down by 16% but their level increased by 2%. This suggests that with caffeine, their processing speed slowed down, but their arm capacity and accuracy slightly improved. This could possibly be a result of inconsistent caffeine consumption, varying caffeine tolerance levels or side effects such as jitteriness or reduced focus. Previous research has shown that moderate consumers sometimes experience more disruptive effects than habitual consumers, as their bodies are less accustomed to the psychological effects of caffeine. (22)

A rare consumer who had caffeinated beverages around two times a week showed a moderate improvement in speed of 8%; however, their level declined by 4%. This mixed outcome reflects that caffeine helped these participants stay more alert and increased their processing speed, but reduced their accuracy and possibly their memory capacity. On the other hand, the group that never or occasionally consumed caffeinated beverages showed a modest improvement of 3% in their speed, and the highest improvement in level (7%). These findings suggest that occasional consumers may be the most sensitive to the effects of caffeine. This allowed them to benefit the most from caffeine, enabling them to focus sharply. This is probably because their body have not yet developed tolerance against caffeine, which habitual consumers have. Prior research also supports this idea, proving that low-frequency users often showcase the most measurable outcomes. (23)

Conclusion

This study indicates that caffeine consumption had a subtle yet measurable effect on STM performance in teenage girls. Caffeine particularly played a role in tasks requiring quick recall and attention; however, its role was not that dramatic when it came to STM span capacity or accuracy.

The findings suggest that while caffeine may provide a temporary edge in cognitive tasks, it cannot be heavily relied on as a primary tool to aid in academic performance or as a memory enhancer. These results also highlight the complexity of caffeine's role in teenagers' cognitions, suggesting it is neither a guaranteed enhancer nor an entirely ineffective stimulant.

The results show that caffeine is not a “fit for all”. Caffeine's effect on STM highly depends on how often it is consumed. This study concludes that caffeine affects all consumers differently; for some, it may improve processing speed, for others, accuracy and for the rest, both or neither. Depending on the frequency of caffeine consumption and an individual's tolerance, it may also cause drawbacks, as experienced by moderate consumers.

The findings of this study suggest that caffeine is most useful at extremes. Participants who consumed caffeine daily and participants who never consumed caffeine showed the most measurable positive outcomes. They were susceptible to caffeine effects.

Limitations of the study

Small sample size: The sample size was considerably small, with only 24 participants participating in the experiment in total and 12 in each group. Therefore, the results of this study cannot be generalised.

Reliance on self-reported survey data: The baseline information on caffeine habits was self-reported, which may or may not include biased, overestimation or underestimation of caffeine intake.

Controlled dose: The participants were administered a controlled dose of 80mg/day, which falls within the moderate dosage range, so habitual consumers may have already developed tolerance to it.

External factors: Factors such as sleep patterns, diets, stress, and differences in daily routine may have influenced participants' performance.

Future

Future research should be conducted with a bigger and more diverse sample. The study should consist of long-term testing and comparison of different caffeine dosages. Participants should be monitored so that external factors can be controlled. This would help further clarify the sole role of caffeine on the STM of female teenagers and give us a clearer picture.

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Analyzing Correlations Between the S&P 500 and NIFTY 500 During Black Swan Events: A Predictive Modeling Approach By Jayden Leung

Abstract

Global financial integration has heightened the interdependence of markets, particularly between developed and emerging economies. This study investigates how black swan events, such as the dot-com bubble burst, the 2008 Global Financial Crisis, and the COVID-19 pandemic, have shaped the correlation between the U.S. S&P 500 and India's NIFTY 500 indices. Using daily return data from 1999–2021, rolling correlations over 30-, 60-, and 90-day windows were calculated and compared against moving averages to identify contagion effects during crises. The research further frames correlation prediction as a supervised classification task, employing Random Forest, XGBoost, and Multinomial Logistic Regression to forecast 10-day-ahead correlation regimes. Results indicate that correlations consistently intensify during global shocks, reducing diversification benefits for investors when they seek it the most. Among the models, the 60-day rolling correlation proved most effective, with Random Forest and XGBoost outperforming linear models but also displaying risks of overfitting. These findings demonstrate that correlation spikes can serve as early-warning indicators of economic instability and underscore the limitations of diversification during crises. The study contributes to understanding the transmission of financial shocks across borders and offers insights for investors, regulators, and policymakers in managing systemic risk.

Introduction

With the rise of globalization in the late 20th century, the worldwide integration of national economies has never been as broad or as deep. Indeed, as the Federal Reserve Bank of Chicago states, through trade, increased capital flows, investment networks, and supply chain linkages, the interdependency of international markets has reshaped the global financial system. Emerging markets like India, now the fastest growing major economy in the world, have integrated into the global economy through its expanding role in global supply chains and increased capital inflows via foreign direct investment (FDI). For this reason, India is positioned to be a primary engine for future global growth. The International Monetary Fund (IMF) projects India's economy to contribute almost 20 percent to global GDP growth over the next 5 years, thus presenting lucrative diversification opportunities for investors.

The NIFTY 500 encompasses the top 500 companies listed on the National Stock Exchange of India (NSE) and represents about 96.5% of the total turnover of the Indian Markets. Similarly, the Standard and Poor's 500 (S&P 500) is a stock market index tracking the performance of 500 large companies listed on major U.S. stock exchanges, representing the leading indicator of U.S. market performance.

While integration of India's market into the world economy is rising, investors will be more inclined to participate in its growth as more money will gravitate towards the NIFTY 500. India is also seen by many as a low correlation market compared to the developed markets like

the US and the S&P 500, but this paper highlights the potential hazard of that notion, especially during major financial shocks and disruptions, which can be characterized as “black swan events”. Consequently, these extreme shocks, reflected in the movements of the S&P 500, acted as a global contagion channel, through which financial crises in one part of the world transmitted across other financial markets. Although the NIFTY 500 often exhibits synchronized movements caused by shared macroeconomic conditions, geopolitical events, and investor sentiment with other global stock indices, black swan events have historically amplified normal correlation. Within the current scholarly conversation, there is limited research on how black swan events specifically alter S&P500-NIFTY500 correlations. Thus, this paper hypothesizes that the historical correlation between the S&P 500 and NIFTY 500 indices strengthens in the short term, and the price movements between both indices become increasingly connected.

Scholars have attempted to quantify the connectedness between stock markets around the world. According to Paliwal & Saxena (2023), this relationship is termed “dynamic interdependence,” and it consists of four measures of market dynamic linkage: “cause and effect” (causality), “spillover effect” (both market volatility and return), “cointegration,” and “connectedness”. For this paper, we classify correlation as falling under “connectedness” as correlation is a short-run linear co-movement measure.

In the scope of this research, this paper seeks to explore the following research question: *How have black swan events, such as the 2008 Global Financial Crisis and the 2020 COVID-19 pandemic, shaped the historical correlation between the S&P 500 and NIFTY 500?* Furthermore, this paper will investigate the extent to which sudden increases in correlation can serve as an early warning signal for financial crises. Lastly, this study will employ various machine learning (ML) models to predict the 30/60/90-day rolling correlation in 10 days after the last available date in our respective dataset (2020-11-04). By investigating predictive machine-based models to anticipate shifts in correlation regimes, the study hopes to demonstrate how such models can be useful for investors in their decision-making process to anticipate and adjust strategies in order to minimize potential losses during these extreme events.

The study hopes to contribute to the discussion on two very different stock indices from two very different economies - the most developed market in the United States and a developing market in India - that will be more prominent, interconnected, and strategic as the world moves towards a multi-polar order headlined by these two nations. Whereas global investors aim for portfolio diversification in the NIFTY500 is expected to reduce risk, this study aims to highlight and warn that black swan events and major financial shocks can make it ineffective.

Literature Review

In recent years, the growing interdependence of global stock markets has drawn significant attention, driven both by the rise of new economic powers and the impact of global macroeconomic events such as financial crises and pandemics. This literature review synthesizes an extensive body of scholarly research that explores the co-movements, causal relationships, and integration of stock indices across different regions. Furthermore, various studies investigate

the effects of volatility spillovers from one market to another and attempt to use time series analysis to forecast the future movement of various indices.

Numerous studies have explored the linkages between the Indian stock market and global indices, revealing strong cointegration. One study analyzed monthly data (2005–2015) from five major indices (NSE NIFTY, S&P 500, FTSE 100, Nikkei 225, and Hang Seng) using correlation, Johansen cointegration, VECM, and regression models (Marisetty). The study found that NIFTY adjusted more slowly to long-term equilibrium, reflecting its reactive nature to global movements, especially the S&P 500. Similarly, Paliwal and Saxena applied the Granger Causality test to daily S&P 500 and BSE Sensex data, finding bidirectional short-run causality. Dasgupta confirmed this using ARIMA and RNN models, showing that U.S. market movements lead Indian market responses by several days.

Studies have also shown that during periods of global turmoil, previously segmented markets tend to move together as investors reassess risk and seek safety. Manu and Menda confirmed this phenomenon with regression results showing bidirectional movement between global indices and the Indian stock market during major shocks.

In a study of black swan events on stock markets, Phadnis et al. define such global shocks as any period of seven consecutive days during which the difference between the maximum and minimum values of a particular stock exchange is greater than or equal to 10 per cent of the maximum value (114). Using a differing methodology from the study of Phadnis et al., we identified similar structural shocks over the period of 1999 - 2001, displaying an abnormal spike in correlation that differs from the historical trend.

Conversely, several studies note a breakdown in cointegration during crises, as domestic conditions and policy responses cause markets to diverge. Marisetty found that while global indices, especially the S&P 500, explained 96% of variance in NIFTY prices during global movements, short-term divergences persisted due to local factors (6459). Similarly, Ali et al. used ADF tests and VECM to show that although India is closely linked to global markets, domestic factors still drive short-term volatility. Supporting this, a study cited by Paliwal and Saxena found no significant interdependence between the U.S. and Indian markets using the Johansen cointegration test.

Several studies have applied models such as Generalized Autoregressive Conditional Heteroskedasticity (GARCH) to analyze bidirectional volatility spillovers, underscoring the interconnectedness of the Indian and global markets. Johnson Mary used GARCH models to examine volatility clustering, persistence, and spillovers between the NIFTY 500 and S&P 500, finding strong bidirectional effects that intensified during financial crises.

Similarly, Sainath et al. (2023) employed a DCC-GARCH model on daily NIFTY 50 and international index returns, including the S&P 500, revealing that spillovers vary over time, strengthen during crises, and exhibit dynamic asymmetry, with negative shocks strengthening correlations more than positive ones (2).

In forecasting applications, Rahman examined cross-market momentum, finding that daily S&P 500 movements predict next-day NIFTY 50 shifts due to investor sentiment, global

news, and India's short-run inefficiency. The study confirmed that "markets move in tandem during periods of global stress," with momentum strategies performing best during crises (Rahman, 20-21). However, diversification benefits remain limited, as both indices closely mirror each other when shocks occur.

Nagel critiques the growing reliance on complex ML models for stock return prediction, finding that models like neural networks and ensemble methods offer only marginal gains over linear regressions, and that predictive power mainly comes from a few established factors. Overfitting is common despite the use of large datasets with extensive variables.

Based on the extant literature, it can be concluded that a majority of the current scholarly research indicates a high level of market integration among countries and, correspondingly, a short-term increase in correlated movement between the U.S. and Indian stock market indices during black swan events. Few studies, however, attempt to anticipate shifts in correlation regimes in a predictive, forward-looking way. This study wishes to further the discussion of the correlation between the US and Indian stock market indices by employing machine-based learning models to verify past black swan events in order to identify future major financial shocks.

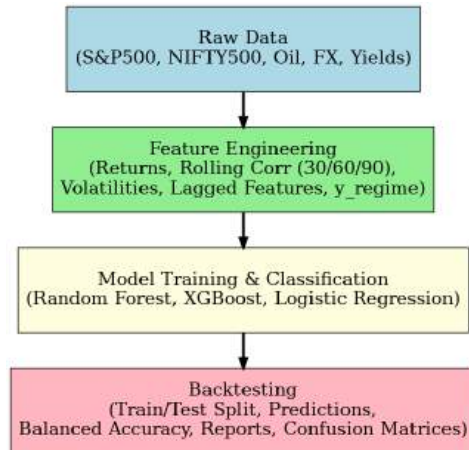
Data and Methodology

In essence, this study turns raw market and macro data into a model-based learning algorithm that classifies two stock market indices' historical trends into correlation regimes and predicts future correlation values. By training three different ML models, this study evaluates their accuracy, explains their performance, and demonstrates which features drive regime shifts.

Specifically, this study adopts an empirical research design to:

1. Examine the historical correlation between the NIFTY 500 and S&P 500, overlaying different moving averages (MA) on the correlation graph to see if the predicted T+10 correlation exceeds the calculated MAs, potentially signaling an early black swan event
2. Backtests and classifies the 30/60/90-day rolling correlations in T+10 days into correlation regimes (high/medium/low)
3. Predict the 30/60/90-day correlation in T+10 days after 2020-11-04

Figure 1. Research Pipeline



The diagram above illustrates the research pipeline, outlining the sequential steps from raw data collection through feature engineering, model training, and backtesting.

Data Collection & Preparation

The data for this study is sourced primarily from Kaggle, a reliable financial database for data science and machine learning. The dataset provides daily equity and macroeconomic data necessary to examine cross-market linkages. Standard preprocessing steps, including cleaning, alignment of time frames, and calculation of returns, were applied to ensure consistency and suitability for correlation analysis.

Daily closing prices of the S&P 500 and NIFTY 50 indices were obtained to calculate rolling correlations over different time windows (30-, 60-, and 90-day). These equity datasets form the foundation for examining cross-market linkages.

Key macroeconomic indicators, such as exchange rates, commodity prices, and interest rate data, were included to capture broader drivers of correlation dynamics. These variables contextualize equity market movements by reflecting global and domestic economic conditions.

An important consideration in defining the period of study is how far back data should be taken to remain relevant to current market dynamics. Although S&P 500 records extend as far back as 1927, such early data are less useful, as structural shifts in the global economy and financial markets would likely reduce predictive accuracy without adding meaningful insight. Instead, a more recent span of 20–25 years, which can be viewed as a distinct phase in macroeconomic history, was deemed more appropriate. Accordingly, the period from 1999 to 2022 was selected, as it captures several major global black swan events and provides a comprehensive basis for examining and identifying potential signals of future crises.

Methodology

The methodology combines visual analysis with machine learning classification to examine cross-market correlation regimes. Time-series charts and moving averages highlight

historical trends and anomalies, while rolling correlations are backtested and classified into high, medium, and low regimes. The approach combines market data (returns, volatility, correlations) with macro drivers (yields, oil, FX, sentiment), and employs three machine learning models (Random Forest, XGBoost, and Multinomial Logistic Regression) to classify regimes and evaluate predictive performance.

Visual analysis through charts such as a time-series line chart helps identify trends, patterns, and anomalies in the selected indices over time. Additionally, with moving averages overlaid, it highlights short-, medium-, and long-term trends in the historical correlation.

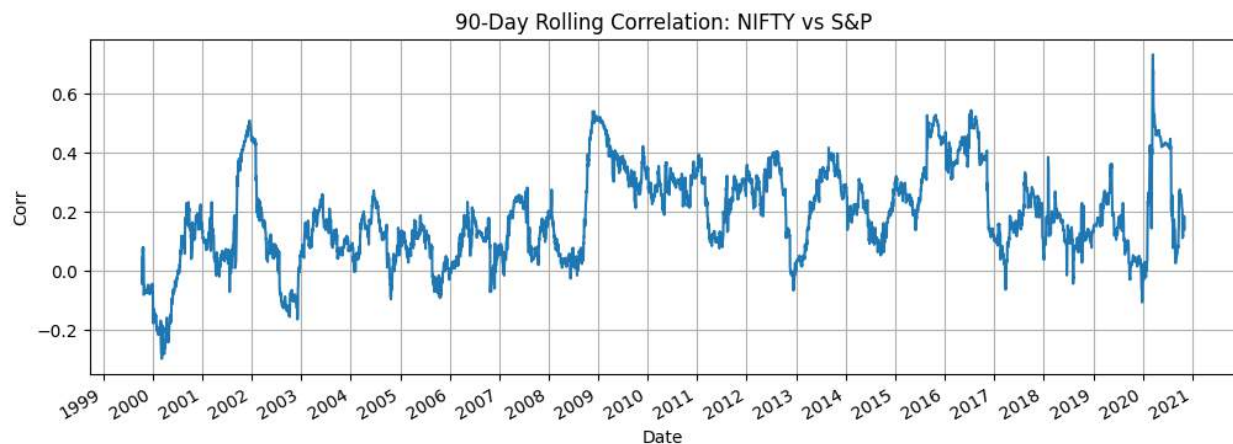
For correlation regime classification and future correlation prediction, the following ML models were used:

- 1. Random Forest: An ensemble of decision trees that improves classification accuracy by averaging multiple randomized models, reducing overfitting.**
- 2. XGBoost: A gradient-boosted decision tree algorithm optimized for speed and performance, effective at capturing nonlinear relationships in financial data.**
- 3. Multinomial Logistic Regression: A statistical model that generalizes logistic regression to classify outcomes into more than two categories, providing interpretable baseline results.**

Results and Discussion

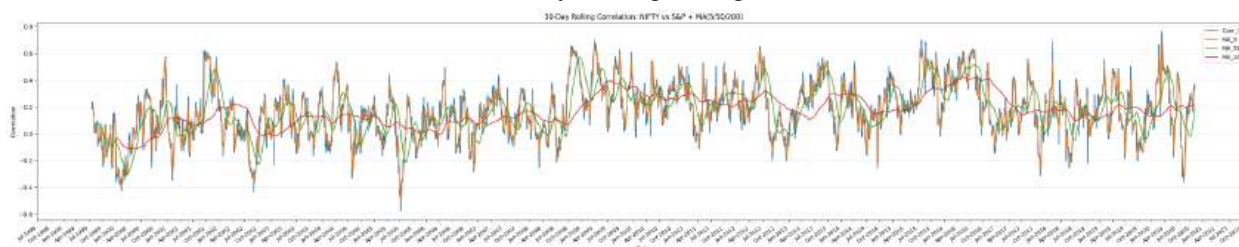
In the first stage of the analysis, we examined how major black swan events shaped the historical co-movement between the S&P 500 and NIFTY 500. Rolling correlations were computed using 30-, 60-, and 90-day windows, with moving averages of varying lengths overlaid to filter out high-frequency noise and reveal underlying long-term trends. This approach provides insight into both short- and long-term shifts in correlation dynamics, offering a clearer view of how crises influenced cross-market linkages.

Figure 2. 90-Day Rolling Correlation: NIFTY 500 vs S&P 500



Source: Author's calculations.

Figure 3. 30-Day Rolling Correlation between S&P 500 and NIFTY 500 (1999–2021) with 5-day, 50-day, and 200-day Moving Averages



Source: Author's calculations.

Figure 4. 60-Day Rolling Correlation between S&P 500 and NIFTY 500 (1999–2021) with 5-day, 50-day, and 200-day Moving Averages



Source: Author's calculations.

Figure 5. 90-Day Rolling Correlation between S&P 500 and NIFTY 500 (1999–2021) with 5-day, 50-day, and 200-day Moving Averages



Source: Author's calculations.

From our correlation analysis, we observed a general trend: the correlation between the U.S. and Indian markets is generally positive but fluctuates significantly over time, highlighting periods of both divergence and strong co-movement (as shown in Figure 1). Using this, we observed and defined three correlation regimes: **high** ($\text{Corr} \geq 0.5$), **medium** ($0 \leq \text{Corr} < 0.5$), and **low** ($\text{Corr} < 0$). While moderate correlations suggest partial integration, sharp spikes during global crises demonstrate that black swan events drive stronger synchronization across developed and emerging markets. Thus, the classification of black swan events was determined to be a correlation increase of 0.5 ticks or greater. As such, this heightened co-movement reflects the globalization of capital flows, where large shifts in one market tend to have momentum, rapidly spilling over into other markets. Consequently, diversification between U.S. and Indian equities is least effective precisely when investors most need it: during systemic downturns.

Six major black swan events were identified, corresponding to the high-correlation band and aligning with the key months examined in this analysis:

1. **Dot-Com Bubble Burst** (February – May 2000)
2. **9/11 Terrorist Attacks** (January – September 2001)
3. **The Great Financial Crisis** (December – October 2008)
4. **U.S. Debt Ceiling Crisis & Fed Taper Tantrum** (May – August 2013)
5. **Chinese Stock Market Turbulence - “Black Monday”** (June – September 2015)
6. **COVID-19 Pandemic** (January – March 2020)

It is noteworthy that between 1999 and 2008, the mean correlation hovered around 0.0, indicating relatively weak linkages between the S&P 500 and NIFTY. Furthermore, occasional dips into negative correlation highlighted periods of local divergence, where domestic factors in India temporarily decoupled from global market movements. However, following the 2008 financial crisis, the mean correlation increased to approximately 0.2, accompanied by both higher peaks and higher troughs. After this period, the rolling correlation rarely dipped below zero, suggesting limited divergence and a persistent joint movement. While India is a developing market, the NSE NIFTY has shown a strong, steady upward trend from 2008 to 2023, reflecting its increasing integration into the global financial system and exposure to global investor sentiments. Consequently, the growing trend in co-movement observed would suggest that in times of global marketwide movements (e.g., post-Dot-Com bubble, post-2008 recovery, post-COVID surge), the NIFTY 500 could exhibit a higher degree of correlation. This structural shift implies that U.S. and Indian equity markets became increasingly integrated as a result of India’s economic expansion and capital market growth. It could also be the result of large swaths of money being created by global central banks like the Federal Reserve in combating the Great Financial Crisis, which ultimately led investors to think they were diversifying portfolios by allocating to different markets globally. But when an acute financial disruption wakes investors up, they tend to drain money from the system in not just the U.S. market but also in other markets and perhaps hedge in U.S. dollars as a safe haven during such crises.

In Figures 3, 4, and 5, which depict a time-series line chart of the 30-, 60-, and 90-day rolling correlations with moving average overlays, the five spikes in correlation observed are associated with a prior convergence of the correlation’s moving average. Thus, we tested whether sudden increases in correlation between NIFTY and S&P 500 can serve as early-warning signals for financial crises by comparing the time-series chart to the Bloomberg graphs. For instance, if the two markets become highly synchronized, it could indicate growing systemic risk for a potential black swan event. Figure 2 shows erratic fluctuations caused by the shorter rolling window’s sensitivity to noise, making black swan events harder to identify. Therefore, Figures 3 and 4 were used to assess whether the convergence of moving averages with historical correlation precedes market declines, testing its potential as an indicator of black swan events.

In short, after an analysis of each black swan event, comparing the correlation graph with the index graph to determine whether or not the correlation spike precedes index price sell-offs,

our findings show that the correlation surge correctly predicted five out of the six observed black swan events. Ultimately, this suggests that there is a reason to use ML models to predict future correlation shifts and potential black swan events going forward.

Dot Com Bubble Burst (2000)

Figure 6. NIFTY 500 Performance (2000) with 50-, 100-, and 200-Day Moving Averages



Source: Bloomberg Finance L.P.

Comparing Figure 6 with Figures 2 and 5, the rolling correlation between the S&P 500 and NIFTY 500 rose sharply between April and July 2000, with the moving average converging in April before reversing. Contrary to expectation, however, the NIFTY 500 had already peaked in late February and dropped about 33% by April, meaning the correlation spike captured only part of the drop. The Fed's rate hikes that year likely accelerated capital outflows from emerging markets. By the time correlation peaked, most of the sell-off had already occurred, suggesting this crisis could not have been predicted. Even so, the episode showed that U.S. shocks already had a strong influence on Indian equities, despite limited financial integration at the time.

9/11 (2001)

Figure 7. NIFTY 500 Performance (2001) with 50-, 100-, and 200-Day Moving Averages

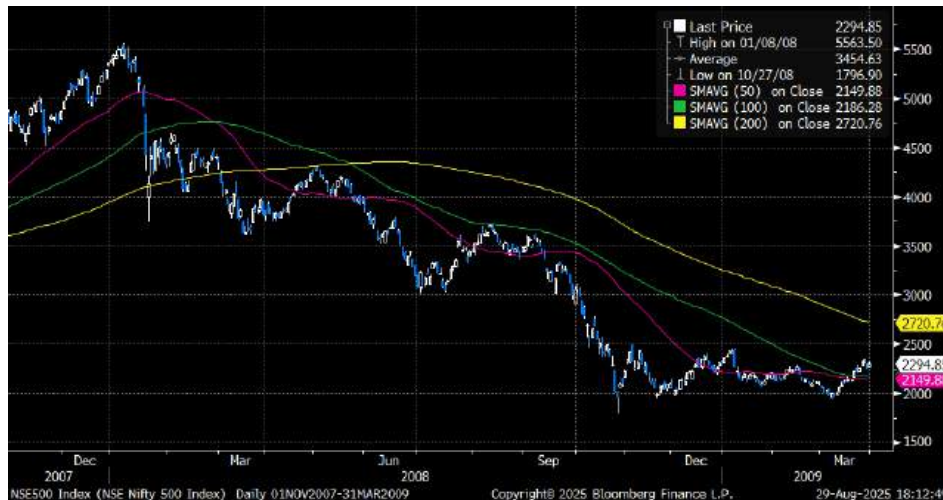


Source: Bloomberg Finance L.P.

Similar to the Dot Com Bust, we observed that the downturn of the NIFTY 500 began after the correlation spike in early 2001. Comparing Figure 7 to Figures 2 and 5, we noticed that the correlation began to make a sharp upward reversal in July, but by then, the NIFTY 500 had already made a significant drop in early February. However, this early selloff was likely triggered by a global recession and the aftermath of the dot-com bubble collapse, which caused a depreciation of the Indian Rupee. In early September, when the attacks occurred, this caused another drop in the NIFTY. Though being a geographically distant emerging market, the index reacted negatively, with Foreign Institutional Investors (FIIs) rapidly reducing exposure to Indian equities amid heightened global uncertainty. Thus, the correlation spike and moving average convergence in July may have anticipated the post-9/11 market crash.

Great Financial Crisis (2008)

Figure 8. NIFTY 500 Performance (2008) with 50-, 100-, and 200-Day Moving Averages



Source: Bloomberg Finance L.P.

The 2008 Global Financial Crisis shows that while the NIFTY 500 began declining as early as January 2008, falling nearly 70% from its peak of 5,563 to 1,796 in October due to foreign investor outflows, the sharp correlation spike did not appear until October, around the collapse of Lehman Brothers (Figures 2 and 5). This suggests the selloff in Indian equities was already underway, but the surge in correlation preceded the peak phase of global market turmoil. Unlike in 2000, when correlation spikes lagged market declines, the 2008 spike provided a timely signal of contagion, marking the moment when diversification benefits disappeared and U.S. shocks rapidly transmitted to Indian markets.

U.S. Debt Ceiling Crisis & Fed Taper Tantrum (2013)

Figure 9. NIFTY 500 Performance (2013) with 50-, 100-, and 200-Day Moving Averages



Source: Bloomberg Finance L.P.

Correlation dynamics in 2013 show a sharp spike around January (Figures 2 and 5), coinciding with rising volatility in both U.S. and Indian markets. In May, the Fed's announcement triggered outflows from emerging markets as investors anticipated higher U.S. rates, driving the NIFTY 500 down nearly 20% by late August alongside U.S. market turbulence. By the 2010s, Indian equities had become highly sensitive to U.S. monetary policy and fiscal uncertainty, with correlation spikes now moving in sync with downturns. The moving average convergence in January preceded the NIFTY's decline, while its reversal in August marked the rebound. Thus, the 2013 event shows how U.S. volatility spillovers reached India almost instantly, with elevated correlations acting as early warnings of contagion risk.

Chinese Stock Market Turbulence - “Black Monday” (2015)

Figure 10. NIFTY 500 Performance (2015) with 50-, 100-, and 200-Day Moving Averages



Source: Bloomberg Finance L.P.

As shown in Figures 2 and 5, the correlation spiked from April to June 2015, reflecting a sudden synchronization between U.S. and Indian equities. At the same time, a downturn occurred alongside global risk aversion as investors were shaken by the Chinese stock market crash. Between June and August, the Shanghai Composite Index lost nearly 40% of its value, and on August 24, Chinese equities plunged 8.5% a single day, triggering widespread panic globally. The S&P 500 followed, and this volatility shock quickly spread to emerging markets, including India. Therefore, the 2015 spike preceded the NIFTY's and S&P's decline by a few months, corroborating our conclusion that correlation shifts can provide an early warning of black swan events and the associated price downturns in both emerging and developed market indices.

COVID-19 Pandemic (2020)

Figure 11. NIFTY 500 Performance (2020) with 50-, 100-, and 200-Day Moving Averages



Source: Bloomberg Finance L.P.

As seen in Figure 11 with Figures 2 and 5, the correlation between the NIFTY 500 and the S&P 500 surged dramatically from January - March 2020, just before and during the 50% decline in the NIFTY. This correlation spike revealed how quickly financial linkages tightened under systemic stress, with Indian equities moving almost in lockstep with U.S. markets as global investors fled to safety. Similar to 2008 and 2013, the pandemic underscores that diversification benefits were vanishing, effectively foreshadowing the depth of the selloff in the NIFTY. While unprecedented fiscal and monetary stimulus fueled a rapid rebound by mid-2020 (reflected in the sharp downward reversal in correlation), the COVID-19 crash demonstrated that spikes in cross-market correlation can serve as a powerful predictor of potential black swan events, allowing analysts to identify when local markets are most vulnerable to global shocks.

The following subsection presents the machine learning classification results of correlation regimes, highlighting how Random Forest, XGBoost, and Multinomial Logistic Regression performed in identifying high, medium, and low correlation bands.

Note: Detailed confusion matrices and feature importance charts are provided in Appendix B.

MODEL 1: Random Forest (RF) Results

Balanced Accuracy (Corr_30/Corr_90): **0.4245**

Table 1. RF Classification Report - Corr_30/Corr_90

Class	Precision	Recall	F1-Score	Support
High	0.100	0.158	0.122	19

Low	0.333	0.164	0.220	55
Med	0.935	0.952	0.943	937
Accuracy			0.849	1011
Macro Avg	0.456	0.425	0.428	1011
Weighted Avg	0.887	0.894	0.889	1011

Source: Author's calculations.

Balanced Accuracy (Corr_60): **1.000**

Table 2. RF Classification Report - Corr_60

Class	Precision	Recall	F1-Score	Support
High	1.000	1.000	1.000	19
Low	1.000	1.000	1.000	55
Med	1.000	1.000	1.000	939
Accuracy			1.000	1013
Macro Avg	1.000	1.000	1.000	1013
Weighted Avg	1.000	1.000	1.000	1013

Source: Author's calculations.

Random Forest struggled on the 30- and 90-day windows, misclassifying most “high” and “low” regimes as “medium,” with a weak balanced accuracy of 0.4245. On the 60-day window, however, it achieved perfect classification, showing strong capability when regimes are more distinctly separated. Still, this reliance on the 60-day horizon highlights inconsistency, as performance dropped sharply outside the optimal window, suggesting that while Random Forest can excel under the right conditions, its predictive power depends heavily on the stability of the regime structure.

MODEL 2: XGBoost Results

Balanced Accuracy (Corr_30/Corr_90): **0.7165**

Table 3. XGBoost Classification Report - Corr_30/Corr_90

Class	Precision	Recall	F1-Score	Support

High	0.159	0.579	0.250	19
Low	0.235	0.782	0.361	55
Med	0.974	0.789	0.871	937
Accuracy			0.784	1011
Macro Avg	0.456	0.716	0.494	1011
Weighted Avg	0.918	0.784	0.832	1011

Source: Author's calculations.

Balanced Accuracy (Corr_60): **0.9996**

Table 4. XGBoost Classification Report - Corr_60

Class	Precision	Recall	F1-Score	Support
High	1.000	1.000	1.000	19
Low	0.982	1.000	0.991	55
Med	1.000	0.999	0.999	939
Accuracy			0.999	1013
Macro Avg	0.994	1.000	0.997	1013
Weighted Avg	0.999	0.999	0.999	1013

Source: Author's calculations.

XGBoost performed better than Random Forest on the 30- and 90-day windows, especially in recalling the “low” regime, though precision for minority classes was weak. In the 60-day window, the model was nearly flawless, reaching a balanced accuracy of 0.9996. Yet, like Random Forest, its strength was concentrated on the optimal horizon, with weaker reliability across noisier windows. This demonstrates that XGBoost is powerful for regime classification when structural separations are clear, but less reliable in unstable contexts.

MODEL 3: Multinomial Logistic Regression (MLR) Results

Balanced Accuracy (Corr_30/Corr_90): **0.7676**

Table 5. MLR Classification Report - Corr_30/Corr_90

Class	Precision	Recall	F1-Score	Support

High	0.171	0.684	0.274	19
Low	0.246	0.836	0.380	55
Med	0.980	0.782	0.870	937
Accuracy			0.738	1011
Macro Avg	0.466	0.768	0.508	1011
Weighted Avg	0.925	0.783	0.832	1011

Source: Author's calculations.

Balanced Accuracy (Corr_60): **0.9647**

Table 6. MLR Classification Report - Corr_60

Class	Precision	Recall	F1-Score	Support
High	0.346	0.947	0.507	19
Low	0.775	1.000	0.873	55
Med	0.999	0.947	0.972	939
Accuracy			0.950	1013
Macro Avg	0.707	0.965	0.784	1013
Weighted Avg	0.974	0.950	0.958	1013

Source: Author's calculations.

MLR outperformed both Random Forest and XGBoost on the 30- and 90-day windows, with stronger recall for minority regimes despite low precision. In the 60-day window, it also performed strongly (balanced accuracy: 0.9647), though slightly below the tree-based models. Unlike the ensemble methods, MLR was more balanced across horizons, but its weakness lies in low precision for rare regimes, leading to false positives. Despite this, even simple models can capture regime dynamics effectively, offering robustness across windows despite reduced precision in minority cases.

Predicted Correlation Values

The results below show predicted correlation values **10 days after 2020-11-04** across three rolling windows. For most models, predictions decline as the window length increases, since longer windows smooth out fluctuations in the correlation curve (Figures 2–4). On average, forecasts converge around 0.175, reflecting values close to the historical mean correlation.

1. 30-Day Predicted Rolling Correlations (T+10 Day):
 - a. RF Predicted 30-Day Correlation: **0.2306**
 - b. LogReg Predicted 30-Day Correlation: **0.1737**
 - c. XGBoost Predicted 30-Day Correlation: **0.2084**
2. 60-Day Predicted Rolling Correlations (T+10 Days):
 - a. RF Predicted 60-Day Correlation: **0.1682**
 - b. LogReg Predicted 60-Day Correlation: **0.1642**
 - c. XGBoost Predicted 60-Day Correlation: **0.1623**
3. 90-Day Predicted Rolling Correlations (T+10 Days):
 - a. RF Predicted 60-Day Correlation: **0.1719**
 - b. LogReg Predicted 60-Day Correlation: **0.1381**
 - c. XGBoost Predicted 60-Day Correlation: **0.1602**

Overall, the results show that while all models performed best on the 60-day window, their strengths varied. Random Forest was flawless under this horizon but inconsistent elsewhere, XGBoost combined near-perfect accuracy with stronger adaptability across windows, and MLR was the most balanced but less precise. Taken together, XGBoost stands out as the most effective model, offering both accuracy and reliability in classifying correlation regimes. We concluded that it is the most suitable model for extending regime classification into prediction applications, where detecting shifts in correlation can serve as an early warning of black swan events.

Future Implications

For investors, contrary to common belief amongst investors that developing markets present a low-correlated asset to diversify from US equities, the strong correlation between developed and emerging market indices like the S&P 500 and NIFTY 500 during big financial shocks highlights that such diversification does not yield the desired results. After the financial crisis, many central banks across the globe are acting in tandem by lowering rates and pumping money into the system, and with all that money flowing to big investors (e.g., hedge funds, asset management firms, etc.), this causes correlation between indices to spike because financial firms are buying and selling in multiple markets/currencies. Therefore, the results of this study caution investors when diversifying across multiple markets that may be tightly integrated. During black swan events, this study corroborates with past studies that heightened correlation does happen during times of extreme financial stress, and a predictive model that can lend a hand in identifying future major price drawdowns would greatly benefit an investor's hedging strategies.

Research Limitations

In our study, we employed a relatively large financial dataset (given limited resources and computing power) with many predictor variables. However, the results highlighted the fact that the large set of factors (where some may not be useful) was integrated into complex ML models that may have performed well in-sample, but failed out-of-sample. Specifically, the very high performance in Corr_60 models (balanced accuracy close to 1.0) suggests possible overfitting.

Since markets are noisy, dynamic, and influenced by many unobserved variables, this suggests the models might be memorizing historical data rather than learning true predictive relationships. While the tree-based models look perfect statistically, they likely do not reflect real-world predictive reliability.

The data collected for macroeconomic features may not have been compatible or helpful when added to the dataset. Due to limitations on the time period of the data collected, the computed correlation only spans till 2020-11-04. Thus, we cannot see the correlation in the 5-year gap to the current date. In terms of frequency, this study was limited to using daily returns, but higher-frequency data (intraday) might show more accurate dynamics in correlation spikes around crisis events. Furthermore, there may be an underlying emerging market bias as the NIFTY 500 itself is not as globally integrated in the early years (1999–2005), so correlation patterns might not fully reflect global contagion mechanisms at the time.

For investors, even if correlations spike before crises, investors may not be able to trade or hedge quickly enough to avoid losses. This would require high-frequency data and other time-series models (e.g., ARIMA, VAR, LSTM RNNs) beyond the scope of this study. Even with our predictive machine-based learning approach to highlight shifts in correlation regimes in predicting future financial shocks, this predictive model should be used as one of many tools and inputs in a holistic, multi-prong decision approach for an investor's hedging strategies.

Opportunities for Future Research

Future studies can expand beyond analyzing the correlation between the S&P 500 and NIFTY 500. Applying the same methodology but including other emerging markets (e.g., Nikkei 225, Shanghai Composite, etc.). This would test whether correlation spikes as early-warning signals are unique to the U.S.–India connection or more universal across other emerging markets. Future studies can also test macroeconomic shocks (interest rates, oil, FX) as potential underlying drivers for causality to correlation spikes. To quantify the predictive power of correlation spikes, examining how many days/weeks correlation spikes typically precede declines in emerging markets may be indicative of such. Out-of-sample crisis testing can also be explored by testing models on crises not included in the training data (e.g., Russia-Ukraine war, Trump Liberation Day Tariffs, post-2025 economic shocks). This would directly measure whether correlation spikes can act as generalizable early-warning signals not present in the test sample. Future studies can also explore alternative ML approaches with deep learning models like LSTMs or transformers, which are better at capturing time dependencies. These models could be compared against traditional econometric tools like Granger causality or VAR variance decomposition to see which method is better at explaining correlation dynamics. Finally, this study can be extended to simulate how an investor could use these findings to adjust asset allocation. For example, if correlation exceeds X% for Y consecutive days, the trading model can shift portfolio weight away from emerging markets.

Conclusion

In conclusion, this study examined the historical correlation between the S&P 500 and NIFTY 500 during major black swan events between 1999 and 2021, and evaluated whether sudden spikes in correlation can serve as early-warning signals of systemic risk. By analyzing 30-, 60-, and 90-day rolling correlations with moving average overlays, the research demonstrated that correlations consistently rise during global crises (rolling correlation spike of at least 0.5), limiting diversification benefits for investors. Machine learning models, including Random Forest, XGBoost, and Multinomial Logistic Regression, were then applied to classify correlation regimes and forecast 10-day ahead values. Across all models, the 60-day rolling correlation proved most effective, achieving far higher balanced accuracy than the noisier 30-day or overly smoothed 90-day windows. These findings confirm that correlation spikes align closely with downturns in Indian equities and, in some cases, precede them, underscoring their potential as indicators of contagion and a potential major financial shock that may have outsized negative drawdowns in portfolio value. Ultimately, this project argues that there is a heightened correlation between S&P 500 and NIFTY 500 during black swan events, and by quantifying a correlation band to identify potential correlation regime shifts that signify major financial shocks, the study highlights both the promise and the limitations of using correlation-based machine learning models to anticipate financial crises, while offering practical insights into the risks of global market integration for investors.

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Exploring the Neurocircuitry of Comorbid Depression and Anxiety By Khadija Koubaa

Abstract

This review explores the comorbidity of major depressive disorder (MDD) and generalised anxiety disorder (GAD), two of the most prevalent and co-occurrent mood disorders, in order to determine whether they represent distinct disorders or overlapping neurological dysfunctions manifesting in different symptom presentations. Findings in this paper were synthesized from published neuroimaging and clinical studies to date reviewing the brain regions involved in the neurocircuitry of MDD and GAD in both comorbid and non-comorbid patients. Results suggest both shared and disorder-specific abnormalities, though there was notable heterogeneity in findings due to diagnostic variability, methodology, and sample characteristics. The review concludes that current evidence is insufficient to determine whether these pathologies are distinct or manifestations of the same neurobiological substrate. Future research should prioritise longitudinal studies, data-driven classification methods for improved diagnostic clarity, and further investigation of understudied brain regions (e.g., bed nucleus of the stria terminalis, nucleus accumbens) to determine disorder-specific versus transdiagnostic features.

Introduction

Major depressive disorder (MDD) and generalized anxiety disorder (GAD) are prevalent mood and anxiety disorders with the highest rates of comorbidity. Epidemiological studies (Kessler et al. 1915-23) have shown that 67% of patients diagnosed with lifetime GAD report MDD in retrospect, while 20% of patients with MDD report GAD retrospectively. These high rates call into question whether these disorders are truly distinct or whether they have the same underlying deficits that manifest in different symptom presentations.

While some studies (Sunderland et al. 1113-23 ; Zbozinek et al. 1065-71) suggest that the high comorbidity rates directly result from the current diagnosis system. According to the DSM-IV-TR, four of the symptoms of GAD and MDD overlap: psychomotor agitation, fatigue, difficulty sleeping, and difficulty concentrating. Other studies attribute these rates to a genetic correlation between MDD and GAD (Gorwood 27-33 ; Kendler et al. 453-462). This review paper explores the underlying neurobiology of these disorders in order to better understand issues of comorbidity.

Neurocircuitry of MDD

Neuroimaging studies have shown that MDD is associated with structural and functional anomalies in various key limbic and paralimbic brain regions. These changes could be exacerbated by exposure to stress, thus enhancing vulnerability for this disorder (Lucassen et al. 109-35). The following section reviews the structural changes associated with the brain regions involved in the neurocircuitry of depression, as well as their regional activation and functional connectivity.

The nucleus accumbens, also known as NAc, is a key nodal region in the brain. It is involved in the processing of rewarding stimuli as well as the integration of input from various brain regions such as the prefrontal cortex (PFC), the hippocampus, and the amygdala (Xu et al. 1420028). Although it is not subject to volumetric abnormalities, the NAc demonstrates reduced activity in patients diagnosed with MDD. Circuit dysfunction in the VTA-NAc pathway leads to impaired reward processing that is believed to mediate core symptoms of MDD such as anhedonia, dysphoria, and a decrease in motivational approach behavior (Ploski et al. 109-17). The hypothalamic-pituitary-adrenal (HPA) axis is a neuroendocrine system composed of three organs: the hypothalamus, the pituitary gland, and the adrenal glands. This system regulates the body's response to stress by releasing hormones, namely cortisol, into the bloodstream (Leistner et al. 55-64). HPA axis hyper-responsiveness, and therefore hypersecretion of cortisol, have generally been associated with MDD (Kirkegaard et al. 253-64). It is worth noting, however, that disease progression may not have an impact on altered HPA axis activity, since patients with chronic MDD have shown no significant alteration in the functioning of their HPA axis (Watson et al. 1021-28).

The hippocampus is a temporal lobe structure often associated with the consolidation of memories, both contextual and spatial (Burgess et al. 625-641). This structure is also involved in the regulation of HPA axis activity (Jacobson et al. 118-134). Chronic stress may lead to dysfunctions regarding this regulation. In this situation, the hippocampus would be unable to dampen the HPA axis, causing its hyperactivity and leading to a breakdown in the stress-regulation mechanism. Notably, studies have shown that alteration in hippocampal volume is intimately linked with MDD. A reduction in hippocampal volume has been noticed in patients with MDD (Campbell et al. 598-607; Arnone et al. 1393-1404). Whether the reduction in hippocampal volume is a cause or consequence of MDD is an issue that has often been subject to debate. The two theories may not be mutually exclusive, since some studies indicate that these volumetric reductions could be a risk factor for developing MDD (Chen et al. 270-76; Carballedo et al. 569-78), while a meta-analysis reveals that hippocampal volume reductions are exhibited by patients who have suffered from MDD for at least two years and that have had more than one episode (Mckinnon et al. 41-45).

The amygdala is a small yet vital part of the limbic system. It is responsible for emotional and behavioral control, memory formation, social cognition, and the mediation of information between prefrontal-temporal association cortices and the hypothalamus (Abu Hassan). This structure is most commonly associated with fear and anxiety regulation. Neuroimaging studies have revealed that baseline activity in the amygdala is elevated in patients with MDD, and its response to affective stimuli is heightened as well (Drevets et al. 93-118; Hamilton et al. 993-1000). This elevation in baseline activity has been associated with symptom severity (Drevets et al. 3628-41). Meta-analyses also show a significant decrease in amygdala volume among unmedicated patients with depression (Hamilton et al. 993-1000). Glucocorticoid excitotoxicity induced by stress, presumed to be the cause of hippocampal atrophy in psychiatric illnesses (Sapolsky et al., 775-765), may be at the root of amygdalar volume loss in MDD.

The prefrontal cortex (PFC) is a brain region that is extensively connected with cortical and subcortical areas. The PFC has many functions, namely executive function, emotional regulation, decision-making, and social cognition. It exerts top-down regulation through neurological pathways, regulating multiple brain regions such as the amygdala, which is believed to be the cause of negative emotional suppression (Ploski et al. 109-117). The PFC can be divided into two sections: the ventromedial PFC (vmPFC), present amongst all mammals and associated with the regulation of affective behavior, and the dorsolateral prefrontal cortex (dlPFC), believed to be present in primates only, and often linked to executive function (Smaers et al. 714-20). Lower PFC volume has been observed in patients with MDD which is believed to be caused by synaptic loss, neural atrophy, and the decrease of glial cell count (Kang et al. 1413-15). This decrease in PFC volume, as well as dysfunctional activity and connectivity, has been linked to the severity of MDD symptoms (Holmes et al. 1529). Enhanced vmPFC activity has been observed as well, and correlated with reduced activity in the amygdala (Johnstone et al. 8874-84; Koenigs et al. 14980-86).

Functional connectivity describes the connection between two regions of the brain and measures the statistical relationship between their activity, and demonstrates how different regions in the same functional network connect with each other. The reward circuit in the brain is a prime example of this. The ventral tegmental area (VTA) comprises dopaminergic neurons that transmit stimuli to the nucleus accumbens (NAc). The VTA-NAc circuit is of paramount importance to the recognition and initiation of consumption of environmental rewards, as well as the response to aversive stimuli. These VTA dopaminergic regions innervate multiple brain regions, such as the PFC, amygdala, and hippocampus (Russo et al. 609-25). These “brain-reward regions” are all interconnected via complex pathways, making them a functional network. Since MDD has been associated with several structural and functional anomalies in these limbic and paralimbic structures, it is unsurprising that the functional network would be affected as a whole due to functional connectivity, hindering its ability to process reward and assess the outcomes of different choices effectively.

Several other functional networks are of relevance to the neurocircuitry of MDD, such as the frontoparietal network (FN), associated with top-down attentional and emotional regulation, the default network (DN), involved in internally oriented attention, the dorsal attention network (DAN), linked to externally oriented attention, and the affective network (AN) and ventral attention network (VAN), involved in emotional processing and salient event-monitoring (Buckner et al. 2322-45). Deficits in cognitive and affective functioning may be exacerbated by specific patterns of network dysfunction, therefore potentially underlying clinical symptoms of mood disorders such as MDD. Individuals with MDD exhibit abnormal connectivity both within and between functional networks (Alexopoulos et al. 56-65). Meta-analysis has shown hypoconnectivity within the FN as well as hypoconnectivity between the FN and the DAN, the AN and the DN, and the VAN, FN and DN. It has also shown hyperconnectivity within the DN and hyperconnectivity between the FN and control regions of the DN. Reduced connectivity within the FN and impaired connectivity between the DN and the DAN may reveal depressive

biases toward isolation and rumination at the expense of interacting with the outside world. Furthermore, altered connectivity between the FN and the VAN may be associated with deficits regarding mood regulation (Kaiser et al. 603-11).

Neurocircuitry of GAD

Generalised anxiety disorder is a pathology that is highly prevalent in the general population. It is characterised by chronic anxiety and excessive worrying (American Psychiatric Association). This disorder is often associated with impaired social functioning, a reduced quality of life, as well as high mortality and morbidity. The neuroimaging literature exploring this disorder is significantly less extensive than the literature covering MDD. Further research is required in order to better understand the underlying mechanisms of this disorder. Nevertheless, we know that anxiety disorders are closely correlated with anomalies in the fear circuit, which includes but is not limited to the amygdala, the hippocampus, certain regions of the prefrontal cortex, and the bed nucleus of the stria terminalis (BNST) (Cui et al). The following section will explore the structural changes associated with the brain regions involved in the neurocircuitry of generalised anxiety disorder, as well as their regional activation and functional connectivity.

Some neuroimaging studies report an increase in amygdala volume or grey matter density among patients suffering from GAD (Makovac et al. 789-95; Suor et al. 83-89). Such structural abnormalities have been linked to heightened threat sensitivity and emotional dysregulation. Conversely, other studies have shown no significant volumetric variations or even a decrease in amygdala volume (Hayano et al. 266-76; Massana et al. 80-90). This heterogeneity in neurobiological responses could be due to a myriad of different factors such as severity, medication, and comorbidities. Inconsistencies also extend to functional changes. Numerous fMRI findings report an increase in amygdala reactivity to threat-related stimuli (Bishop et al. 10364-68; Etkin et al. 1043-55; Stein et al. 318-27) , which could be interpreted as a neural correlate between increased threat perception and anxiety symptoms. Variability extends to connectivity patterns as well, such as amygdala-prefrontal connectivity. Some studies show a decreased functional connectivity between the amygdala and vmPC, suggesting an impairment in top-down regulation of fear and anxiety. However, other studies found no change in connectivity or even increased connectivity between those two areas (Porta-Casteras et al. 211-19; Gold et al. 917-26) , highlighting context specificity.

Structural and functional changes in the PFC have also been reported. Several studies show reduced grey matter volume and cortical thickness in various regions of the PFC such as the OFC and the dPFC in GAD patients (Jeong et al. 852-56; Strawn et al. 154-60). Conversely, some research reports increased volume in subgroups such as the vmPFC and the dmPFC (Gold et al. 2423-33; Schienle et al. 303-07). Functional neuroimaging studies report diverging findings. Hypoactivation in regions of the PFC involved in emotional regulation, such as the vmPFC during tasks involving emotional processing, has been reported in some studies (Simpson et al. 688-93; Bishop et al. 10364-68) while others show increased activity in regions such as the dmPFC (Straube et al. ; Bishop 307-16). This could be interpreted as diminished

top-down regulation in fear and anxiety responses. The variability in findings may be attributed to the context, tasks and conditions under which the various studies were conducted. The subregions visualised also differ across studies, with some focusing on the vmPFC's role in emotional regulations, while others examine the dlPFC's role in cognitive control. This may influence the findings on whether PFC activity increases or decreases among GAD patients.

It is also relevant to mention the effects of inflammation on brain connectivity, particularly the amygdala-vmpFC pathway, in the context of mood and anxiety disorders. Extensive research has shown that an increase in inflammation, particularly elevated peripheral inflammatory markers such as cytokines and CRP, correlates with reduced connectivity between these two regions (for review, see Mehta et al. 725-30). This diminished connectivity is often associated with hyperarousal and heightened anxiety symptoms. The degree of inflammation is closely related to the severity of anxiety symptoms. Higher inflammatory marker levels are linked to greater connectivity impairment in amygdala-vmpFC coupling (Felger 533-58). These findings suggest that inflammation may impair top down regulation exerted by the PFC over the amygdala and other limbic regions, though longitudinal studies are needed to establish causality and assess whether the reduction of inflammation can restore normal connectivity.

While studies on structural connectivity changes in the BNST are limited, research utilising diffusing tensor imaging and probabilistic tractography to map out the BNST's connectivity across the human brain have shown that it is connected to key regions involved in stress and anxiety such as the amygdala, hypothalamus, and other limbic areas taking part in processing emotions, making the BNST a crucial locus in the neurocircuitry underlying mood disorders such as GAD (Avery et al. 311-23). Although human neuroimaging evidence is scarce, emerging studies indicate that BNST connectivity patterns may differ in patients with mood and anxiety disorders, though the majority of the research focuses on larger brain regions or more accessible structures such as the amygdala, with less emphasis on the BNST itself. Detailed human studies on the BNST show that it is much larger in humans compared to other creatures such as rodents (for review, see Boucher et al. 451-58). The variability and limited consensus regarding the connectivity alterations related to mood and anxiety disorder in the BNST stems partly from methodological differences such as imaging resolution and analysis techniques as well as the small size of the BNST, which impedes consistent measurements.

Comorbidity

The comorbidity of GAD and MDD is highly prevalent. According to epidemiological data, up to 90% of patients with GAD experience at least one other mental illness during their lifetime, most notably MDD at approximately 67%, whereas 20% of patients with lifelong MDD report comorbid GAD. The comorbidity of GAD and MDD is often associated with greater severity of symptoms, poorer treatment response, and exacerbated emotional dysregulation (Nutt et al. 109-18). Longitudinal data shows that anxiety symptoms tend to precede depressive episodes, which suggests that anxiety symptoms could serve as an early indicator or risk factor

for subsequent development of MDD, possibly due to shared stress-related neurobiological mechanisms (Saha et al. 757-70).

DSM-5 criteria (American Psychiatric Association) of MDD and GAD show several similarities and differences. While GAD is characterized by uncontrollable excessive worry and MDD by persistent depressed mood (longer than 6 months) and a loss of pleasure and interest known as anhedonia, there is considerable symptom overlap between these two disorders. These symptoms include fatigue, irritability, sleep disturbances, and difficulty concentrating. This overlap can complicate differential diagnosis due to symptom blending and diagnostic ambiguity.

The variability and overlap in symptom presentation increases the risk of misdiagnosis, which can influence neurobiological findings in research, as different studies might include heterogeneous samples, potentially contributing to inconsistent neuroimaging and biological findings. Treatment efficacy can be impacted as well due to under-recognition of depression in anxious individuals and vice-versa.

As discussed in the previous sections, neuroimaging studies investigating MDD and GAD reveal significant heterogeneity in their findings, which complicates the understanding of their neurobiological underpinnings, and does not offer decisive evidence as to whether these disorders are two separate pathologies or whether they are the same neurobiological disorder with differing symptom presentations. Some studies report increased amygdala volume and hyperactivity for both MDD and GAD, while other research finds no volumetric differences and decreased amygdala activity. Similarly, structural and functional abnormalities within the PFC have been documented extensively for both disorders. Some research reports decreased activity, while others report no significant change or even hyperactivity. This may be due to context dependent modulation and methodological disparities such as imaging resolution, analysis thresholds, sample characteristics, as well as subregions focused on in each research paper (vmPFC, dlPFC, etc). Hippocampal volume reductions are frequently reported but not universally observed. MDD and GAD exhibit similar neurobiological patterns such as alterations in serotonergic pathways and HPA axis dysfunctions, and disrupted amygdala-PFC connectivity which affects top-down control over limbic regions (for review, see sections I and II).

While the amygdala might serve as a transdiagnostic region involved in both disorders, studies examining comorbid cases indicate that comorbid GAD and MDD often exhibit increased activation in bilateral insula as well as frontal regions such as the frontal and middle gyrus (Cao et al.). It is, however, relevant to mention that brain regions such as the BNST and the NAc that play a vital role in GAD and MDD respectively have not yet been explored in the context of comorbidity, and therefore are missing from most of the literature. These regions could serve as important neurobiological markers of the interplay between anxiety and mood symptoms within the same individual in future research. Though outside the scope of this paper, it is relevant to note that studies show shared genetic liability for both disorders which might contribute to comorbidity (for review, see Mather et al. 619-27).

Conclusion

In summary, neurobiological studies on the comorbidity of MDD and GAD reveal substantial heterogeneity in findings. Some papers have reported shared alterations in brain regions such as the PFC and amygdala, though findings are often inconsistent due to variability in study designs. Structural neuroimaging studies show both overlapping and distinct neural patterns in MDD and GAD. As of now, it is impossible to determine whether these disorders are neurobiologically distinct or one and the same. That is due to research limitations such as variations in diagnostic criteria, mixed samples (age, symptom severity, comorbidities, medication status), methodological variability (MRI, fMRI, PET, etc), neglect of comorbidities, as well as lack of longitudinal and developmental data.

Future research direction should prioritize study designs that enable direct comparisons between diagnostic groups in order to elucidate disorder-specific versus transdiagnostic features. Latent profile analysis (LPA) could facilitate the data-driven creation of subgroups based on symptom patterns and neurobiological markers, transcending traditional categorical diagnosis. Bottom-up approaches which start from detailed symptom profiles to derive classifications, could also be promising in that regard. Advancing our understanding of MDD and GAD comorbidity demands a focus on more integrative and comparative strategies with an emphasis on data-driven approaches in order to truly determine if these disorders are truly distinct.

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Long-term Impacts of Chapter 11 Bankruptcy By Kayla Peng

Abstract

This paper examines the benefits of Chapter 11 bankruptcy and assesses its long-term impact on corporations in the United States. Is Chapter 11 a good solution for a business in financial distress, and how does it compare to its alternatives? The research draws on a combination of scholarly articles, non-academic literature, and case studies to examine how Chapter 11 works and its effects on corporations in the real world. The research reveals that restructuring has effectively helped a large portion of firms maintain operations while providing them the opportunity to pay back their debts to the benefit of their owners and investors alike. Although Chapter 11 requires strategic decisions to successfully navigate a precarious time of distress due to issues such as paying high professional fees or negotiating with creditors for approval, many businesses have favored Chapter 11 over Chapter 7, an alternative that invariably results in the complete liquidation of assets. An in-depth case study of American fast food restaurant Sbarro illustrated how restructuring has helped a business successfully recover from financial distress. In the long term, the protection of Chapter 11 bankruptcy grants them protection and leeway to optimize profits and cut costs, allowing distressed firms a second chance to stay in business and achieve success.

Background

What is Chapter 11 bankruptcy?

When a business encounters financial distress, they can experience signs such as defaulting on loans, poor EBITDA (earnings before interest, taxes, depreciation, and amortization), and insolvency. They have several options going forward. One common mechanism is to leverage the US bankruptcy code.

Chapter 11 is one type of bankruptcy under the US bankruptcy code, which is designed to allow businesses with debt to reorganize their finances and continue operations under court supervision. Chapter 11 is unlike Chapter 7 bankruptcy, which involves liquidating, or converting assets into cash to settle obligations in terms of paying debts and distributing remaining value to owners. The firm may also be acquired by another willing firm. However, of the three options, Chapter 11 uniquely allows for benefits that allow the business—now the debtor—to continue operations.

Chapter 11 has beneficial implications beyond what is outlined in the bankruptcy code. By helping businesses avoid shutdown, Chapter 11 has helped preserve jobs, keep suppliers in business, and stabilize local economies. When a firm is afforded the potential for recovery, significant losses can be avoided that would otherwise disrupt the livelihoods that depend on its continuity (*Chapter 11 - Bankruptcy Basics*, n.d.).

Process of Chapter 11

The process of Chapter 11 begins with the filing of a voluntary petition by debtors or eligible creditors, which details the debtors' financial position and interests. This creates a bankruptcy estate that puts into effect an automatic stay, which halts collection efforts and lawsuits.

Meanwhile, the debtor becomes the Debtor in Possession (DIP). The debtor will have the ability to obtain high-cost bridge funding to sustain operations, and the financier acquires the role to work alongside the business in managing operations, reports, claims, and estate property as a trustee while proceedings continue. Automotive manufacturer General Motors was able to turn around its business after the Global Financial Crisis in 2008 thanks to the government's support. After the Treasury granted a bridge loan under the Troubled Assets Relief Program (TARP), the administration provided DIP financing which helped General Motors expedite the bankruptcy process. As a prominent US auto manufacturer, the government's intervention helped to save the auto industry and economy.

The debtor has a 120-day exclusivity period to propose a reorganization plan outlining claims and obligations. The details of the plan include the order of claims in terms of creditor repayment and meet legal standards in terms of feasibility. The typical classes of the creditor hierarchy are as follows: secured creditors, priority unsecured creditors, general unsecured creditors, and equity security holders.

They will then give creditors a disclosure statement to evaluate the plan and to vote. If rejected, Chapter 11 fails and the firm must either turn to Chapter 7 or have the case completely dismissed. However, if the creditors have granted approval, the debtor will enact the plan for restructuring and begin emerging from bankruptcy

Methodology

This paper aims to examine the benefits and risks as well as the long-term implications of Chapter 11 bankruptcy for financially distressed businesses in the United States. The study is structured around a case-based and process-oriented analysis, using publicly available data, academic literature, and legal documentation to evaluate the strategic applications of Chapter 11. Because the Chapter 11 process is highly technical, statistics and real-life examples were used to illustrate the steps of the process.

1. Literature Review

A literature review was conducted to help examine existing research on Chapter 11 bankruptcy. This research was based on scholarly articles obtained from JSTOR and Google Scholars. Key terms such as "Chapter 11 bankruptcy," "debt restructuring," "turnaround," and "reorganization" were used to find these articles. Relevance, in terms of the research question was prioritized, followed closely by recency of publishing date.

Non-scholarly articles were used to elaborate on the lack of scholarly information on the basics of key topics. These sources included a combination of educational finance websites and

government records. Because academic research on foundational topics was limited, non-scholarly sources needed to be consulted to provide context for the subjects discussed in this paper. Additionally, news articles from outlets such as PR Newswire and NBC News were used to provide context on recent bankruptcy events and current performance of the companies referenced in the case studies.

Common points between authors were a discussion about whether Chapter 11 was worth pursuing for firms considering the risk of incurring high costs as well as its efficiency of resources for those involved. Through statistics and examples, this paper seeks to provide an answer to whether Chapter 11 is truly a beneficial option to firms and the market as a whole.

2. Case Study

To further demonstrate the information discussed in the paper, case studies were used to provide examples of how Chapter 11 and related topics are applied in the real world. Keeping in mind the paper's focus on the long-term effects of Chapter 11, older cases such as Sbarro and General Motors were analyzed throughout the paper. These case studies were leveraged to highlight different aspects of the Chapter 11 bankruptcy proceedings and clarify more complicated concepts.

Analysis

Benefits of Chapter 11

Chapter 11 is designed to support the business during a time of distress. The court provisions of Chapter 11 can help optimize the capital structure, allow leeway for fixed costs, and provide ways for the debtor to adjust operations for profitability.

Chapter 11 can be beneficial in that it enables the debtor to cut costs and get out of leases and expenses that could further burden the firm's ability to make profits. In March of 2014, when pizza chain Sbarro was struggling to keep up with the costs of high leases at the shopping mall food courts, it filed for Chapter 11 bankruptcy. This decision freed Sbarro from the responsibility of paying leases under court supervision while also giving it time to restructure and devise a plan for a turnover. Sbarro was able to use that time to reduce expenses and focus their business outside of shopping malls by moving their company headquarters, closing less profitable locations, and aiming towards rebranding their image for modern preferences. (Kroll).

The reorganization allowed by Chapter 11 permits businesses to sell assets through a court-supervised process known as a Section 363 sale, which allows the debtor to sell assets "free and clear" of liens, claims, and encumbrances. This means that the asset can be owned without debts or other legal commitments. Although arduous and challenging, this legal protection can make the assets more attractive to buyers, because they are able to acquire them without inheriting the seller's liabilities. For example, the former General Motors—"Old GM"—filed for Chapter 11 in 2009, selling much of its assets to a new entity, the new General Motors—"New GM". By taking advantage of the "free and clear" condition of Section 363 sales, most liabilities and substantial assets were retained by Old GM, which later liquidated

(Angelich). Meanwhile, important assets were transferred to the New GM, allowing General Motors to safely maintain its brand in the face of a financial crisis through clever strategic maneuvers under the provisions of the Chapter 11 bankruptcy code.

As part of the recapitalization process, firms may also consider rights offerings, a form of equity financing where existing shareholders are given the opportunity to purchase additional shares, often at a discount. Rights offerings can raise capital while minimizing dilution and preserving shareholder alignment during reorganization.

Restructuring can also include converting debt to equity, which is a process that reduces the firm's financial leverage and lowers the cost of capital. By exchanging debt obligations for ownership shares, the debtor can eliminate the need to make fixed interest payments, thereby improving cash flow and reducing default risk. Additionally, the debtor's balance sheet can also be adjusted by decreasing liabilities and increasing equity, making the firm more attractive to new investors. A lower debt burden may improve the company's credit, and, therefore provide better financing options.

These changes give businesses breathing room to adjust, allowing them to cut unnecessary costs and reorganize business models. The effects of restructuring have proven to show net future benefits as 58% of the companies that file for Chapter 11 bankruptcy report significant increases in operating income. Similar success could be found in the case of General Motors. After submitting its second, more aggressive restructuring plan and re-emerging, the New GM made a profit in 2010 for the first time in six years, and in the fall of 2011, its credit rating was upgraded (Nygaard, 2022).

Risks of Chapter 11

Chapter 11 can offer many benefits to the debtor in terms of continuing operations; however, it also comes with potential risks, such as costly fees, loss of ownership, and loss of profitability and resources, especially in the short term. These risks can threaten the firm's ability to emerge from bankruptcy, and as a result, the debtor must navigate Chapter 11 strategically for a successful recovery.

Chapter 11, unlike other forms of bankruptcy, does not forgive the debt; instead, it works by significantly adjusting operating procedures to increase profitability and pay off the debt. At the same time, however, the business must pay costly fees for lawyers and consulting. According to vLex, the average debtor spends \$500,000 on lawyers, and creditors spend another \$230,000, with professional fees representing about 1.8% of the distressed firm's total assets, and up to 5% in some instances (Dirman, 2021). Although paying in installments can alleviate the burden, this can still place a toll on the business recovering from its debts, especially in a stressful financial crisis.

Additionally, the debtor must adhere to the reorganization plan and make decisions according to court approval. If not specified in the plan, the debtor is not allowed to expand operations or sell assets. They are also not allowed to take on new loans after filing for Chapter

11. All the while, they must share a greater portion of its ownership with a trustee, while appealing to the creditors for its approval.

The Chapter 11 process may also negatively impact the business' profitability. First, the initial filing for bankruptcy, along with the stigma associated with it, can make businesses appear less appealing to potential and existing investors. New potential investors evaluating similar companies might see this as a stain on their resume and choose to invest their capital into a different company. In addition to losing capital, the company is at risk of not receiving the full market value of its assets due to the distressed nature of the sale and the need for a quick liquidation.

However, these reputational repercussions extend beyond lost capital. The process can hurt the company's workforce. As outlined in their restructuring plan, to recover their profits, GM had to commit to eliminating healthcare benefits and reducing pension plans for certain employees (Nygaard, 2022). Due to the uncertainty associated with bankruptcy, many employees begin leaving an at-risk company months or years before bankruptcy, which can cause a company to lose valuable workers. "The median reorganizing Chapter 11 firm loses roughly 10% of total headcount (aggregate departures net of new arrivals) by the time it leaves bankruptcy protection" (Ellias, 2024). During the changes made to minimize costs and optimize profits, a business' potential turnaround may be hindered by the costs of Chapter 11, which ultimately emphasizes the need for strong leadership and effective reorganization in order to counter these risks.

Strategic Alternatives to Chapter 11

However, in addition to Chapter 11, there are other paths businesses can take in the face of bankruptcy depending on their situation. For example, some businesses may be acquired by a larger, more financially stable company. Mergers and acquisitions allow the target firm to preserve parts of its operations, retain jobs, and potentially realize higher asset values compared to liquidation. Buyers may seek to acquire the distressed firm's intellectual property, customer base, or operational infrastructure at a discount. From the seller's perspective, this pathway can serve as a soft landing, and it may offer better outcomes for creditors and stakeholders than Chapter 7 liquidation. If the distressed company lacks the resources or leadership to reorganize on its own, an acquisition can be preferable to Chapter 11 by allowing the firm to continue business under the support of a larger firm. However, this alternative can often result in a loss of ownership and control over the company.

On the other hand, debtors may have no choice but to turn to liquidation if they are unable to present a viable reorganization plan or lack the operational basis for continued activity. In this process, the business will stop operations and sell off its assets to repay creditors. Debtors typically undergo Chapter 7 if they have a limited going-concern value or if those liabilities overwhelmingly exceed assets. Although this option leads to the end of business operations, it may still offer creditors a more predictable and timely recovery than prolonged Chapter 11

proceedings. Liquidation is much less desirable and often seen as a last resort for companies, resulting in complete and permanent financial closure.

The Role of Tax Policy in Reorganization

Tax implications can also influence the strategic path a debtor might take. Chapter 11 may allow firms to preserve valuable tax attributes such as net operating losses (NOLs), which can offset future taxable income and improve post-emergence profitability. However, certain transactions can trigger limitations, restricting the use of NOLs. Liquidation, on the other hand, often accelerates tax obligations due to the recognition of gains on asset sales.

Outcomes of Chapter 11

Contrary to popular belief, the benefits of Chapter 11 are not limited to a few lucky cases, nor do they often come at the cost of long delays. Successfully reaching an agreement with creditors to begin restructuring is more probable than conventional wisdom indicates. Confirmation rates before the 2005 Amendments were nearly double the commonly accepted number, even when measured by the most naive metrics. Large debtors that at least proposed a plan to reorganize had confirmation rates of two-thirds or more (Warren, Westbrook, 2009). Though successful emergence can prove difficult for the debtor, Chapter 11 can still offer a realistic chance at turnaround with a substantial number of debtors able to emerge from bankruptcy.

Critics have been quick to point out the inefficiencies of the system, accusing the restructuring process of allowing many debtors to take advantage of Chapter 11's protection for years. However, data reveal that most cases, in fact, move at a reasonable pace. Others cite that the costs of Chapter 11 outweigh its benefits, especially in terms of professionals' fees. However, considering that Chapter 11 offers a 40% chance of recovery—with the alternative to restructuring being liquidation and 0% chance of recovery—the cost is reasonable for offering the debtor the opportunity to recover from a dire situation (Lubben, 2012).

So-called “Largest shopping mall-focused restaurant concept in the world,” *Sbarro, Inc.* has suffered from declining mall traffic and rising prices for key ingredients during the Great Recession, and they filed for Chapter 11 bankruptcy on November 17, 2011. After obtaining confirmation of a Chapter 11 plan, the company was left with about \$175 million in outstanding debt with extended maturities. However, Sbarro was forced to apply for second restructuring only two years later. Another commonly contended point by critics is Chapter 11's tendency to result in re-filing. However, thanks to restructuring, Sbarro was able to eliminate much of its huge debt, generating \$4 million in EBITDA, as well as develop a real estate strategy to better manage the locations of its chain expansions and focusing on rebranding its firm. These strategies have helped the company expand in the U.S. and globally to about 800 locations. As of 2024, “52% of Sbarro's restaurants are now outside the United States, up from 48% at the end of 2023” (Pr Newswire, 2025). Restructuring has enabled Sbarro to develop a winning strategy that focuses its efforts on expanding into international markets and different store formats such as

convenience stores. Although not yet at its former glory, Sbarro has been able to recover successfully under Chapter 11 to continue business in more favorable circumstances.

In 2005, struggling home furnishings retailer Linens ‘n Things agreed to be acquired in a \$1.3 billion deal with private equity firm Apollo Management LP (Grant, 2008) after filing for Chapter 11 bankruptcy protection.

Conclusion

Chapter 11 bankruptcy can offer financially distressed businesses a structured pathway to reorganize debt, preserve operations, and improve long-term viability under court supervision. While the process provides critical benefits such as debt restructuring, cost reduction, and strategic asset sales, it also carries substantial risks including high professional fees, ownership dilution, reputational damage, and potential declines in profitability. In certain circumstances, alternatives such as mergers, acquisitions, or liquidation may be actually more appropriate, especially when considering tax implications. Case studies such as Sbarro and General Motors demonstrate both the challenges and potential for recovery, showing that, despite its costs and occasional need for re-filing, restructuring can enable businesses to stabilize and grow. Ultimately, the decision to pursue Chapter 11 requires careful consideration of a firm’s financial position, operational capacity, and long-term goals.

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The Disadvantages of Convolutional Neural Networks in Fire Detection

By Prisha Shah and Jade Babcock-Chi

Abstract

Wildfires have become increasingly prominent in the past couple of years, causing significant damage to land and cities. Current methods of wildfire prediction and mapping are insufficient and still lead to a lot of wildfires going unnoticed until it is too late. Neural networks are currently proposed to be a strong solution for accurate wildfire prediction. Despite CNNs being commonly stated as a prominent solution, they have their disadvantages, such as over-reliance on pixels and lower accuracy and precision. In this paper, we discuss the benefits of RNNs, LSTMs, and mixed systems such as the ConvLSTM model. Using other experiments on wildfire prediction, RNNs have been proposed as the best solution in terms of simplicity and accuracy. Additionally, all of the other models discussed outperformed a CNN-based model in terms of accuracy, precision, and F1 score.

Introduction

In the past five years, there have been many notable wildfires. For example, in Canada in the summer of 2023 and in Los Angeles in 2025. The current solutions for fire prevention include video footage from surveillance cameras or heat detectors, which are unreliable since they only detect large fires, and by that point, a fire would have caused a lot of damage to cities, forests, and their inhabitants. There have been proposed solutions to this issue, which analyze how to predict when a fire is going to happen. With accurate predictions, the fire-likely areas can be patrolled and put out early, so no damage is done. With new advancements in machine learning, there are many solutions proposed to solve wildfires via neural networks in satellites. The most notable solution to wildfire prediction is the incorporation of CNNs (convolutional neural networks) into satellite imagery as a way to gather image data for early wildfire detection. Many have argued that this is the best way to solve the issue with wildfire detection. However, CNNs have their disadvantages, which may make them an unsuitable solution for wildfire detection. In this paper, we will analyze the disadvantages of CNNs and why they would be unreliable in the context of wildfire detection. Additionally, we will discuss the advantages of other neural network and machine learning models that may be a better fit for wildfire detection, such as RNNs or RNN-based algorithms like LSTMs, or a CNN and RNN hybrid system.

Methods

The main issue with wildfire detection is that wildfires vary based on where they start. For example, forest fires are very difficult to detect in the early stages, and when the fire happens, it causes significant damage to soil, crops, and water quality. In industrial factories, fires start based on flammable chemicals such as carbon monoxide and carbon dioxide. (Diaconu) The way fires develop and cause damage depends on the location of the fire. This is

where deep learning techniques come in. As machine learning and deep learning technologies advance, the path for early wildfire detection becomes clearer.

Currently, the protocol for fire detection uses surveillance cameras and detection systems. The problem with these systems is that they cannot differentiate between different particles, such as fire particles or dust. Satellite imagery is significant since it is used to detect weather patterns, changes in climate, GPS systems, etc., therefore satellite imagery is crucial in the turning point of advanced fire detection, using optical thermal sensors to capture imagery and the heat of the fire (Mazzeo et al.). Right now, some of the most notable sensors on satellites are SEVIRI, MODIS, AVHRR, and VIIRS. The main thing in common about all of these sensors is that they gather information using heat detection. These sensors have a low false-positive rate, which is beneficial because there is no time wasted on false alarms. In terms of estimating fires, it uses both long and short-term data. Short-term data may be around a few days or hours, while long-term data may be from weeks to months. While these systems are accurate, the problem comes in when different models have their downsides. Some models don't take into account things like population density or other factors that vary from place to place. Some have low-frequency satellites (polar orbiters) that take too long to process images. There is no single priority score, meaning that analyzing the severity of a fire or a type of fire is a human's responsibility.

Here are common deep learning methods proposed for early wildfire detection in satellite imagery:

1. Convolutional Neural Networks

Convolutional neural networks are the most proposed solution to fire detection. Satellites will take in image data and look for patterns such as smoke in the image (Ghali and Akhloufi). CNNs use supervised learning, learning through labelled data, to know what to look for. Such as the instance of wildfires, the algorithm will look at multiple images of wildfires and normal land. The algorithm will need to see many images to accurately distinguish between "wildfire" and "no wildfire". The incorporation of a CNN in a satellite would mean that the images would be processed in the satellite itself instead of being sent down to Earth.

2. Recurrent Neural Networks

Recurrent neural networks are deep learning models that deal with processing sequential data. Each input in a sequence is dependent on the others, and each input will have its own parameters. The algorithm will then analyze the inputs and give outputs, such as "wildfire" or "no wildfire". The inputs go into a "memory cell" to recall whenever a wildfire is detected. Both RNNs and CNNs will take in image data using hyperspectral imagery, but RNNs will use images and make sequences to see fires. They may take images of an area to analyze a change to see whether a fire is emerging.

3. Long Short-Term Memory Systems

LSTMs are a type of RNN system, except they are designed to remember information for longer periods. LSTMs are designed to take in more complex data, so while a simple RNN algorithm can see a wildfire for a couple of days, an LSTM can look at patterns that span weeks, meaning its memory cell can hold more data. Otherwise, LSTMs are very similar to RNNs in terms of training, besides the fact that LSTMs take a lot longer and are a bigger investment.

4. Mixed-Model Systems

A CNN and RNN-based algorithm hybrid system incorporates both characteristics. For example, the ConvLSTM model will gather both spatial relationship data from the CNNs and the memory cells from the LSTM. Spatial relationships could be looking for things such as typical topography, elevation, or amount of vegetation in a given area, and the memory cell will store the information to build a pattern (Prapas et al., 4). Because these are two different systems into one, it will probably take a lot of time to train, and it will be a more complex algorithm.

With CNNs, the satellite could send alerts faster about any early wildfire signs. Satellites use hyperspectral imagery, which means that the images can capture colors and patterns that current imaging in satellites cannot capture. For example, the images would be able to capture trees, grass, smoke, etc., behind clouds. Additionally, each pixel must be analyzed so that a CNN gets proper data. RNNs work a little bit differently, such as maybe on day one, there was a lot of green vegetation, and on days 2 and 3, the vegetation slowly decreased. Ultimately, RNNs use pattern recognition to find a fire. As part of RNN training, it may use more than 200 locations of emerging fires to accurately detect wildfires on its own. RNNs are supposed to run faster and analyze data fast enough so a wildfire does not get out of control. Even though LSTMs are a variant of RNNs, LSTM models are more advanced in ignoring cloud or shadow patterns in their analysis of a fire pattern. In both RNNs and LSTMs, there is no risk in facing gradient vanishing or exploding while doing long-term analysis, providing a significant benefit in this neural network model.

The benefit of a deep neural network system in satellite imagery is that it would detect and alert to wildfires faster and earlier, preventing a lot of damage. But CNNs, despite being the most talked-about algorithm, have their drawbacks. For example, in a CNN algorithm, each pixel is labelled. CNN algorithms can be “tricked” or “attacked” by purposely manipulating pixels and misrecognizing a situation. These are called adversarial attacks. If an algorithm comes across an image that is slightly different than what it was trained to do, it may incorrectly classify the image (Yang and Silver, 2). For example, if a CNN comes across a wildfire image that shows a different cloud pattern or forest pattern, it may say that there is no wildfire when there is. Additionally, a CNN detects wildfires based on an image, so it would need a lot of images to properly assess any situation. Each forest, each grass field, each desert, and each habitat type is

different. The way a wildfire spreads through these areas varies greatly based on multiple factors. Which means that a CNN would have to take in hundreds of thousands of pictures, and even then, it may not be able to assess each type of habitat. Some CNN algorithms take 10,000 photos to be fully trained (Thanh and Anh).

An RNN or RNN-based system, like LSTMs, could pose a better solution. A CNN does not use the previous input to process any additional inputs, making each input independent of one another, but an RNN uses a previous input and hides it in its “hidden inputs” to use for processing the output, making each input dependent. Here is why an RNN may be a better option. Let's say you have a climate that has unique weather patterns, and it has a possible wildfire sighting. If you use a CNN, then it may only use a picture in one instance to see if there is a potential wildfire, but if you use an RNN, it can capture a series of changes that are abnormal to that specific region, and by using the previous inputs the algorithm can come to a clearer conclusion that there is a wildfire, something that the CNN could not gather with one photo. LSTMs may be an upgraded RNN system in which the algorithm can hold more long-term memory, meaning that if there is a wildfire that may take a couple of weeks for visible signs, the LSTM can take in more pictures and make a longer sequence to spot a wildfire.

A mixed model also provides its benefits. A CNN model on its own does have great benefits, such as, for example, a CNN has been used for semantic segmentation, which tells not only what the subject is but also where the subject is located. The algorithm will color the pictures based on what each object is, such as coloring the trees green and the sky blue, to make the picture easier to analyze. Using a mixed model, you can combine the semantic segmentation of a CNN model and incorporate it into an RNN or LSTM model, so each segment can have its own semantic segmentation. Additionally, there have been some other proposed mixed models, such as the ConvLSTM model. The benefit of this model is the spatial relationship, a characteristic of CNNs, which will tell the algorithm if the fire is close to trees or if there are clouds in the way. Then it will store those observations in the memory cells. The cons of a mixed model, on the other hand, include that it is very costly and its design is very complex, which could deter companies from installing these into their satellites. They will also need a lot more training in labelling pixels and segmenting, which also means more time.

Results

The first experiment was conducted by the IAASARS National Observatory of Athens. They compared CNNs, LSTMs, and ConvLSTMs for satellites to observe wildfires in parts of Greece. The researchers used MODIS for this experiment. MODIS (Moderate Resolution Imaging Spectroradiometer) is a camera sensor on NASA satellites. These will detect heat, gain land cover, vegetation data, cloud, and temperature data, and any smoke or dust present. They used MODIS to gather basic data, including weather patterns, road density, population density, land cover, topography, and previously wildfire-impacted areas. They gathered this data to gain an overall understanding of wildfire patterns in Greece, then they created a machine learning model and did the training data (to teach the models how to analyze inputs), did the validation

data (fine-tuning the models), and then finally gathered the testing data (final execution of the models). In order for the models to accurately spot fires, they added some “control” training for normal areas so the models don’t consistently say “wildfire spotted” for every single picture. Then they create the machine learning models listed above and compare the accuracy of each model. They analyze the input data using four datasets. The pixel dataset is analyzing the pattern in a singular 1 km by 1 km land area, looking for things such as land cover or cloud patterns. They are a 10-day average, so an analogy is that if the dataset takes in 10 different temperatures, it would average the temperatures to one final temperature. Temporal datasets are how a pixel changes over time, so unlike a pixel dataset, a temporal dataset makes a sequence for the 10 days, so in the context of temperature, it would list each temperature given on a day. A spatial dataset looks at a bigger pixel, 25 km by 25 km, but only looks at the data for one day. Finally, a spatio-temporal data set is the fusion of a temporal and spatial dataset, a 25 km by 25 km pixel viewed in sequence for 10 days (Prapas et al, 4).

To dig deeper into each model, the RF (random forest) model incorporates the pixel dataset. It uses the data to predict whether there is a fire or not. Unlike the other main models, this model is not a deep learning model. The temporal model corresponds to the LSTM, the spatial model corresponds to the CNN, and the spatio-temporal model corresponds to the ConvLSTM. They tested four factors for each model: precision (accuracy in correctly identifying fires), recall (how many fires the models catch), F1 score (the overall balance between precision and recall), and the AUROC (models’ ranking areas with wildfires higher than areas without wildfires; the higher the score, the better). Among the deep learning models, the one that had the best recall and F1 score was the LSTM model, with the probabilities being 0.762 and 0.751, respectively. The model with the best AUROC score is the ConvLSTM model, which has a probability of 0.926. The LSTM and ConvLSTM models showcase that the temporal and spatio-temporal data collection method is most beneficial in wildfire spotting (Prapas et al., 4).

Another work from the 34th Canadian Conference on Artificial Intelligence discusses the disadvantages of CNNs under hostile conditions. The first experiment is to test the CNN’s kernel-based inductive bias (when the CNN assumes what the model is before seeing the model). They tested the CNN by feeding it original images and mixed-up images where they changed the order of the pixels. The results showed that CNN models were more impacted than the other models tested. In the second experiment, they only changed one pixel from the original image. While the CNNs performed well on the original images, they had a significant decrease in accuracy for the changed images. The model correctly classified 5683 original images, but it correctly classified only 4207 out of 5683 images. The conclusion reached is that whenever CNN may encounter any adversarial conditions, the algorithm will be under inductive bias and misclassify images due to its overreliance on pixel orientation (Yang and Silver, 5). Involving only temporal-based models, RNNs and LSTMs were tested on effective wildfire mapping using Landsat-8 and MODIS satellite sensors. They used the Gini Index for both the Landsat-8 and MODIS models to see which factors each sensor takes in as most impactful. Landsat-8 took into account temperature (0.2), wind speed (0.15), and topography wetness index (0.13). MODIS

took into account temperature (0.12), TWI (0.098), and slope (0.076). They ran studies on incorporating both sensors into both deep learning models. They tested RNNs in Landsat-8, LSTMs in Landsat-8, RNNs in MODIS, and LSTMs in MODIS. The main difference between the two sensors is that Landsat-8 has a higher resolution, while MODIS has a lower resolution. To analyze which method was best for accurately finding wildfire-prone areas, they used MSE (mean-squared error), meaning lower values were preferable to higher values. The results are broken down into training MSE and validation MSE. Training MSE is how effective the training of the model is, and validation is how effective the model was during testing. On Landsat-8 for LSTMs, the training was 0.172, and for RNNs, it was 0.175. Validation was 0.177 for both RNNs and LSTMs. For MODIS, the training was 0.204 for LSTMs and 0.201 for RNNs. Validation was 0.227 for LSTMs and 0.219 for RNNs. Overall, RNNs were better for MODIS in both training and validation, but LSTMs were better for training in Landsat-8. Both models were equally good for validation in Landsat-8. In terms of measuring AUC (area under the curve for measuring the effectiveness in identifying safe areas), both LSTMs and RNNs performed above 94 percent, with RNNs having slightly greater performances than LSTMs in both sensor models by 1-2 percent. In comparison to a CNN, the CNN has an 87.92 percent accuracy, which is around 6-10 percent less than the RNNs and LSTMs. Overall, both of these models demonstrate great accuracy when it comes to mapping wildfires and identifying which areas are wildfire-prone and safe (Bahadori et al.).

Discussion

In the first experiment, the overall conclusion was that models with temporal or spatio-temporal data performed better than the spatial data sets, meaning that any RNN/LSTM models outperformed the CNN-based models. This is most likely the case because the RNN/LSTM-based models had more data to work with. Whenever they had a time series, they had better accuracy and a high F1 score. If you can only work off one image taken at one time, then the results may be less precise. The RNN will analyze the overall changes to the weather patterns and habitat to see if a fire could arise soon. This is also another reason why temporal-based data is better than spatial data in terms of F1 and precision. If a CNN only gathers data from one picture, it may not be able to tell the major changes in a location. A CNN may only see a normal picture, while an RNN/LSTM-based model sees the signs of a fire risk. Then, in experiment two, the overall disadvantage of CNNs is explained, and while the experiment didn't test wildfire-specific images, it is safe to assume that the conclusion for CNNs' inductive bias and misclassification can do a lot of harm in the context of wildfires. If, for example, a satellite glitches or if the data is compressed, then a CNN can make false positives or false negatives frequently, just like in the study. Unfortunately, with wildfires, we cannot take these risks because a misclassified image can potentially let a fire go undetected and cause preventable damage. In the third experiment, LSTMs and RNNs provide more reasoning as to why these algorithms outperform CNNs. Both of these models were very good when it came to accurately detecting wildfire-prone areas and differentiating between wildfire hazards and safe

areas. But, RNNs slightly outperformed LSTMs. Overall, while both of these models have their pros and cons, they still outperformed a CNN model by a considerable amount. An RNN may be the best solution. Looking specifically into experiment 1, LSTMs outperformed CNNs and the ConvLSTM model in F1 and precision, than any of the other models. If the first experiment used RNNs in their study, they may have seen better results for F1 and precision. This could be because LSTMs are more complex in design than RNNs. RNNs are simpler and faster, meaning that they are worth investing in over a more complex and slower neural network algorithm. If an RNN takes fewer images for MODIS (MODIS used around 230 images while Landsat-8 used around 600), then it would be much easier and less time-consuming to train an RNN model using MODIS, considering RNNs had better results on MODIS than LSTMs. Also, a more complex model would indicate more money spent, so in terms of budgeting, an RNN poses a better solution while also maintaining high accuracy in mapping fire-prone areas.

On the contrary, CNNs pose some benefits in terms of reduced cost and training time. Because CNNs use spatial data, they can analyze warning signs concerning the position of an emerging fire. For example, let's say a satellite missed an area that was showing signs of future wildfires. A CNN model can use one picture, and on the basis of that picture, the algorithm will detect a fire and send help as soon as possible. Additionally, CNNs may not require as much memory compared to an RNN/LSTM. Since the CNN operates on one picture, it doesn't require as much memory training as an RNN/LSTM due to its memory cells that hold knowledge on sequential patterns. Therefore, training time for a CNN is less than an RNN/LSTM. The mixed system, like the ConvLSTM model, provides a decent solution, including the best of both neural networks, but because it is two neural networks in one, it would have a high cost in production and would require a significant amount of training.

Conclusion

Due to the emergence of wildfires and inadequate methods of wildfire prediction, we discussed the benefits of machine learning with regard to satellite imagery. With the emergence of machine learning, neural networks are a very promising solution to wildfire detection using prediction methods via satellite imagery. While CNNs are highly proposed as a good solution, there are many disadvantages to CNNs. CNNs are over-reliant on pixels, only use one image to gather data, and may be less effective in terms of accurate detection of fire-prone areas. RNNs, LSTMs, and mixed systems such as the ConvLSTM model were tested to see which ones may pose a better solution. Overall, all of these models were better than CNNs, RNNs being the best in terms of simplicity and accuracy. Ultimately, CNNs may not be the best neural network for wildfire prediction, and a proposed solution would be to use an RNN-based algorithm instead.

A future experiment that can be conducted to further prove the best neural network algorithm can be an experiment of all four types of neural networks in one specific location with high fire risk, and seeing which model has the best precision and accuracy in wildfire prediction. One location is a forest in a cooler climate, such as Canada, and another is a forest in a warmer climate, such as the Amazon Forest in Brazil. Another type of fire is fires in industrial settings,

specifically settings with high carbon monoxide and carbon dioxide. Finally, the last type of setting is a typical residential area. The residential areas would be categorized into three different types: one in a grassland-type environment, one in a desert-like environment, and another in a tropical/coastal environment. To keep the results most accurate, the only variable changing is the type of deep learning network used in the satellite. The sensor used would be the same for all algorithms. Because MODIS yielded the best results compared to Landsat-8 in precision and accuracy, MODIS would be used for the experiment. Each algorithm will use approximately the same number of images. This experiment would use 100,000 images, most in the wildfire area but some in normal areas as well, in training. The satellite used would be a typical remote sensing satellite used in GEO (Geostationary orbit). Using a typical RNN, a typical CNN, a typical LSTM, and the ConvLSTM model, the network with the best accuracy, precision, and F1 score would be the best network to use in early wildfire detection.

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The Bay Area Housing Crisis By Claire Yu

The San Francisco Bay Area, a global hub of innovation and economic prosperity, is paradoxically home to one of the most severe and prolonged affordable housing crises in the United States. Despite the decades of prosperity that the technology industry has brought to the region since the 1990s, there has been a severe, long-standing imbalance between population growth and housing production (Karlinsky, 2024). Nowhere is this imbalance more visible than in Silicon Valley, where local snapshots reveal the disparity: San Mateo County generated approximately 102,500 jobs while approving only 9,494 homes from 2010 to 2019—a ratio of approximately 11:1 (Sustainable San Mateo County, 2021). Even region-wide analysis finds multiple new jobs per new home over the 2010s, well above a reasonable balance (Bay Area Council Economic Institute/BIA, 2017).

The outcome: a housing market that is increasingly inaccessible to all but the wealthiest households. In 2025, surges in the AI and biotech sectors have further fueled demand—the median home price in Silicon Valley reached approximately \$1.92 million in 2025 (Joint Venture Silicon Valley, 2025), and the San Francisco Case-Shiller index has more than doubled since 2010, demonstrating the long-run price run-up (S&P CoreLogic Case-Shiller via FRED, 2025). Even individuals who rent face unprecedented strain, with about 1 in 10 being severely burdened (spending over 50% of income on rent), and nearly 48% of SF-metro renter households were cost-burdened in 2023 (Turner Center, 2022; San Francisco Chronicle analysis of ACS, 2024).

Immigration, both domestic and international, has contributed to a significant inflow of housing demand in the Bay Area. Silicon Valley, in particular, has seen a dramatic rise in foreign-born residents who now constitute over 34% of San Francisco's population and nearly two-thirds of the technology workforce (Joint Venture Silicon Valley, 2025). Approximately 41% of the Bay Area's population is foreign-born (Pawlowska, 2025). Immigration has exacerbated the demand for already scarce housing, contributing to the skyrocketing costs, as well as the displacement of long-term residents and an increase in homelessness.

This crisis isn't new; however, it has become especially apparent over the past two decades as affordability has plummeted for middle and low-income households. The real question isn't whether there is enough demand for developers to build housing—there clearly is—but why the region has proven to be structurally incapable of meeting that demand. We must look beyond the past few decades, because its roots can be traced back to the late 1940s, reflecting an amalgamation of policies, an ever-changing economy, and ongoing local resistance to growth.

Structural Barriers to Housing Supply in the Bay Area

The Bay Area's housing deficit isn't the product of recent developments, but long-standing structural constraints that continue to determine land use and limit new development. While these measures were initially adopted to manage growth and protect

communities from uncontrolled expansion, they now function as blockages that solidify low-density developmental patterns and discourage affordable housing production.

Exclusionary Zoning

Berkeley became the first city in the nation to implement single-family zoning in 1916, a practice that set a precedent and continued to spread across the region after World War II for years thereafter (Baldasarri and Solomon, 2020). Outward suburban development became increasingly common, which favored single-family homes over dense urban housing. The zoning regulations many municipalities enacted helped entrench these low-density development patterns—mandating large minimum lot sizes, setting minimum unit sizes, and prohibiting multi-family dwellings even on large swaths of residential land near job centers or transit—outpricing lower-income households and communities of color (Menendian et al., 2020). Today, with approximately 85% of developable residential land in the Bay Area zoned exclusively for single-family homes, this suburban land-use model, locked into the region decades ago, proves to be poorly suited to meeting 21st-century housing demand (Ibid).

“Not In My Backyard”

Compounding the zoning ordinances is the pervasive influence of "Not In My Backyard" (NIMBY) activism, where residents and homeowners oppose new developments to preserve the character of their neighborhoods or maintain the value of their properties. NIMBY activists often invoke tenants' rights, affordability, and environmental concerns, but it is, by and large, regarding separate issues that can be impacted: traffic, school quality, and the aesthetics of their neighborhoods (SF Chronicle, 2023). They leverage political channels through methods such as rallying neighbors to attend city council meetings to protest or supporting ballot referenda to curb development (e.g., growth moratoriums, height limits) (Karlinsky, 2024). They also exploit legal methods, utilizing zoning appeals and procedural challenges to delay or scale back proposed projects, thereby creating an artificial scarcity of homes. This activism helped further restrict density in suburban and urban areas, producing policies that impose additional hurdles.

Despite the widely accepted notion of increasing the number of affordable housing units, a project that originally approved for 60 apartments for low-income seniors in Barron Park, Palo Alto, in 2013, amid opposition from neighbors, eventually got turned into an upscale development of new single-family houses with a selling price starting at around \$5 million. The ballot box victory by the neighbors has discouraged other affordable housing projects in Palo Alto (Hansen, 2020)

Although California has implemented bills such as Senate Bill 9 (2021), which allows duplexes on single-family lots, to combat these obstacles, NIMBYism and its effects on housing supply remain strong (Devulapalli, 2023; UC Berkeley Turner Center, 2022).

Environmental Review

Perhaps one of the most discouraging processes for developers is the environmental review. The California Environmental Quality Act (CEQA), passed in 1970, requires all new developments in California to undergo environmental impact assessments to mitigate pollution and the loss of natural habitats. While CEQA was intended to protect the environment, the law's scope has massively expanded and has become a tool for special interests and NIMBY activists to delay housing projects through litigation, often unrelated to environmental or ecological issues (Calton, 2025). One such example of an impacted project would be the 222-unit project next to the West Oakland BART station, which included 16 low-income units. It was delayed for over a year after trade unions appealed its approval under CEQA, arguing the site's environmental review was inadequate—despite offering to drop the appeal if the developer agreed to hire union contractors. Currently, the project's future is uncertain, and it is surrounded by homeless encampments (Talerico, 2025). When projects are delayed, developers incur interest expenses and property taxes, as well as holding costs on the land—all of which accumulate and proliferate project budgets to unreasonable highs. In the Bay Area, CEQA lawsuits extend approval timelines by years and raise costs by 10-20% per project. In 2020 alone, anti-housing CEQA lawsuits challenged nearly 50% of California's annual housing production.

Recent bills and reforms aim to salvage lost time: California's Senate Bill 35 introduces a ministerial approval option, which allows qualifying housing projects to bypass discretionary review and CEQA lawsuits by approving them administratively. In order to qualify, a project must be primarily residential, be located on infill sites near transit, and include a specified share of affordable housing units (Manji, 2023). Despite this streamlining, the overall permitting process remains one of the slowest in the United States. These delays, especially in affordable housing, where financing margins are already thin, are particularly detrimental.

Complexity of the Affordable Housing Problem

Constructing affordable housing is notoriously complicated and expensive; in the Bay Area, these obstacles are compounded by an interlocking web of regulatory barriers and market pressures. The Bay Area has among the highest construction costs in the world, due to the combined burden of land, labor, materials, and fees. The average per-unit cost for below-market-rate housing was \$664,455—considerably higher than the statewide average—with San Francisco County averaging \$737,417 per unit, the highest in the region (Bay Area Council Economic Institute, 2019). Escalating hard costs continue to exacerbate this dilemma, as the inflation-adjusted per-square-foot cost to build multifamily housing in California increased by 25 percent, or \$44 per square foot, between 2008 and 2018 (Raetz et al., 2020). Labor shortages in the Bay Area, driven by its unprecedented high cost of living, have led to increased wages; meanwhile, tariffs have contributed to the rising prices of building materials. Local impact fees also exacerbate project budgets, often in disproportionate numbers to the population being served. For instance, in 2018, per-unit impact fees for a prototypical 100-unit multifamily development project ranged from \$12,000 in Los Angeles to \$75,000 in Fremont, and single-family development projects incurred fees ranging from \$28,000 per home in

Sacramento to a staggering high of \$157,000 in Fremont—over 7 times more than in Los Angeles (Mawhorter et al., 2018). These conditions collectively create a financial environment in which producing affordable housing is far more costly in the Bay Area than almost anywhere else in the United States.

With costs so high, it is nearly impossible to build below-market-rate apartments without external funding. However, affordable projects seldom pull from a singular funding source. Developers are forced to “stack” subsidies from Low-Income Housing Tax Credits (LIHTC), state and local grants, bonds, and federal programs. With each source having distinct applications and reporting requirements, coordinating can delay groundbreaking by years, thus adding holding costs and interest expenses. Tied to public funding sources are also additional regulatory mandates such as union labor agreements, wage requirements, and deeper environmental reviews. There are often additional design requirements as well, which may dictate unit size, accessibility features, or other amenities. These factors drive up per-unit labor costs and overall design complexity, which private, market-rate projects aren’t subject to (Kneebone et al., 2021)

These costs are particularly challenging for affordable housing developers, who must deliver units at below-market prices while shouldering the same or greater cost burdens as market-rate developers.

Why Developers Still Avoid Affordable Housing

Funding for affordable housing projects typically relies on subsidies, tax credits, and public financing to cover the gap between the high costs of development and low sale or rental prices. However, the process for acquiring funding is uncertain and often takes years to solidify in the timeline. Developers are required to secure full funding before breaking ground—a significant undertaking, considering the unpredictability of subsidy approval and the difficulty of assembling funds from multiple public and private sources. Even when subsidies are available, it often takes a year or two to determine if the subsidy funds are approved. As of the end of 2024, 44,723 proposed affordable homes in California were being stalled (Marcus et al., 2025)

Market conditions can fluctuate considerably during such long timelines; delays, uncertainty, and wait times create opportunity costs that hinder investment. For example, Bay Area reports have centered on closing a \$9.7 billion funding gap and achieving an annual production of more than 40,000 affordable homes in 2024 (Hartley, 2024). This is just one instance from the list to illustrate how funding gaps can cause a project to stall after the land-use plan is established.

In real estate, time is money, and the additional delays embedded in the affordable housing approval process make affordable housing less attractive than luxury condominiums or high-end rental developments, where a greater return is anticipated in a shorter time frame. Thus, for developers, the rational economic choice is to pursue projects that provide maximum profit—something affordable housing projects rarely do. This profitability gap is a key reason the private sector has not generated enough affordable housing units, despite the widely acknowledged housing crisis. Addressing these structural barriers in the Bay Area is crucial to

prevent affordable housing from becoming a vexing issue that undermines equity, mobility, and ultimately, urban vitality.

Maximizing Resources: Public Land for Affordable Housing

Policymakers must implement innovative approaches that maximize existing resources to circumvent supply constraints and related regulations, thereby addressing the Bay Area's affordable housing crisis. One of the most promising strategies is the public land for housing strategy. This strategy leverages government-owned underutilized assets, reduces costs, expedites approvals, and yields more equitable outcomes (California HCD, 2024; Home for All San Mateo County, 2024). By focusing on public land, policymakers can also bypass current market obstacles, such as acquiring land at a fair value, while also generating mixed-income neighborhoods (Home for All San Mateo County, 2024).

This strategy supports state efforts, as seen through California's Surplus Land Act, which requires local governments to prioritize affordable housing when disposing of surplus land (California HCD, 2024). The updated guidelines released in 2024 further strengthened enforcement, reporting, and penalties for non-compliance (California HCD, 2024b). Local jurisdictions, such as Oakland, have procedures in place to designate city-owned parcels as surplus, making them available for affordable housing development (Oakland DEOD, 2024).

There is evidence that these policies are effective: Since 2021, surplus and exempt public lands have contributed to the creation of over 28,000 housing units statewide, including 17,000 affordable units (PILP/HCD, 2024). San Francisco has also enacted its own Surplus Public Lands Ordinance, which explicitly targets city-owned property for use in affordable and homeless housing (SF Admin Code, Ch. 23A, 2024).

City-Owned Land

City-owned land is a valuable and underutilized resource in the Bay Area. Local jurisdictions collectively own parcels such as public schools, city halls, community centers, libraries, maintenance yards, and public parking lots—many of which are centrally located and have easier access to existing infrastructure like transit, roads, and other utilities (Home for All San Mateo County, 2024; California HCD, 2024). By setting aside these surplus properties, cities can create additional housing units, especially for low- and moderate-income households (California HCD, 2024b).

Several categories of municipal land have especially strong potential for redevelopment. City halls and community centers, which typically hold large footprints and adjacent open spaces, can be reconfigured to incorporate residential units while keeping their public functions. A notable example is the Downtown Library & Affordable Housing project in Santa Cruz, which combines a new city library, childcare center, and 124 affordable homes within a single vertical mixed-use development on city-owned land (City of Santa Cruz, 2025). Similarly, in Bay Point (Contra Costa County), a county-led plan combines 384 homes with a new 20,000-square-foot public library on the same site, demonstrating how civic amenities and residential development

can be co-located (Contra Costa County, 2023). Even beyond the Bay Area, the Salida del Sol project in San Juan Capistrano demonstrates how affordable housing can be directly integrated with a City Hall facility, setting a precedent as the first in the nation to implement a civic–residential co-location model (NPR, 2024).

Recent projects show the viability of this approach. In Sunnyvale, California, the Meridian Apartments, located at 397 S. Mathilda Avenue, were developed on a city-owned property, progressing from planning to developer selection in roughly two years—an unusually fast timeline (Macasero, 2025). The City used a Request for Qualifications (RFQ) process to identify qualified developers and entered into an Exclusive Negotiating Agreement (ENA), a contract that grants the selected developer exclusive rights to negotiate terms with the City before final approval. This streamlined process helped expedite the project from the surplus designation to groundbreaking (SF YIMBY, 2024). These site types are abundant across the region, with inventories from the California Department of Housing and Community Development (HCD) highlighting thousands of acres of municipal-owned land suitable for housing.

Advantages of using City-owned Land

A key advantage of city-owned land is that it can eliminate or reduce land acquisition costs—one of the most volatile components of housing development. While national data suggest that land typically accounts for about 13–18% of total development costs, in high-cost markets like the Bay Area, land values are substantially higher and can represent an even greater share of overall expenses (Lynch, 2022; Garcia et al., 2023). By leveraging land that is already in civic use—such as city halls, libraries, or community centers—governments can address financial barriers without displacing essential public functions. Cities can pursue vertical or adjacent development, integrating new housing above or alongside government facilities. This model preserves civic services while unlocking underutilized airspace or excess surface area for residential use (Home for All San Mateo County, 2024).

The feasibility benefits are clear. When governments contribute land at no or reduced cost, affordable housing projects become more viable for nonprofit and mission-driven developers who operate on thin margins. Cost savings can be redirected toward deeper affordability levels, including extremely low-income units.

State policy has also moved in this direction. While the Surplus Land Act requires local governments to prioritize affordable housing when disposing of excess property, more recent initiatives encourage co-location strategies that combine civic and residential uses (California HCD, 2024). By reducing or eliminating land acquisition costs and reevaluating the role of government-owned sites, municipalities can expand the supply of affordable housing without needing to purchase scarce and expensive private parcels.

Streamlining Approvals

As the landowner, the government becomes a direct stakeholder, which can help expedite approvals and eliminate any bureaucratic delays. The government's involvement can promote collaboration among city agencies, which may result in a shortened permitting wait. For instance, California's Senate Bill 35 (SB 35), enacted in 2017, establishes a streamlined, ministerial approval process for qualifying housing projects in jurisdictions that are out of compliance with their housing allocation goals (Manji, 2023; Garcia et al., 2017). Under SB 35, eligible developments that meet objective zoning and design standards and include a minimum share of affordable units are exempt from discretionary review and CEQA environmental review (Manji, 2023). For example, in the City of Saratoga, SB 35 qualifying projects with at least 10% affordable units can utilize the streamlined approval process (City of Saratoga SB 35 FAQ).

Because development on public land often already meets the SB 35 requirements (affordability, access to services, existing infrastructure), it is well-positioned to benefit from this streamlined process. Between 2018 and 2021, a statewide total of 156 SB 35s were approved or pending for SB 35 streamlining, totaling over 18,000 units (Manji, 2023). In addition, the SB 35 statute also places time limits for government action, adding certainty (Ibid). City ownership may even mitigate local opposition, as a stakeholder, the city can have the project incorporated into its housing plan and ensure proper alignment with state law more directly than private developers often can.

Allowing Mixed-use Development

Renovating existing city-owned parcels also provides an opportunity for mixed-use development, introducing civic and residential services to create vibrant, mixed-use sites. For example, redeveloping a community center or library can combine ground-floor civic services and upper-level apartments. This model of development can maximize the use of scarce land while also promoting community engagement and increasing access to civic services.

An example of this mixed-use development is the Downtown Library & Affordable Housing project in Santa Cruz. On a city-owned parking lot, featuring a new public library, a childcare facility, and 124 affordable apartments in a one vertical development (City of Santa Cruz, 2025). The library and childcare space are located at the ground level, keeping them visible and accessible to the community, and housing floors are located above. By connecting nonprofit housing developers with city resources, Santa Cruz was able to eliminate land costs, leverage multiple funding sources, and expedite a project that serves both housing and community needs.

Easy Accessible Locations

Many city-owned parcels are not idle lots, but rather active civic or transportation sites that align with transit-oriented development (TOD). Instead of disposing of less-utilized lands, more cities and public transit agencies are overlaying housing above or next to existing public functions. By building adjacent BART stations, Caltrain stations, and major bus corridors, governments can reduce reliance on cars, increase ridership, and thus create more environmentally sustainable cities.

San Francisco issued a Request for Proposals (RFP) for 266 4th Street in August 2017, a parcel located just above the Yerba Buena/Moscone Muni station, to create a mixed-use development featuring approximately 85 affordable homes and ground-floor retail, while maintaining transit operations (MOHCD, 2017). This model demonstrates how public agencies can unlock the housing potential of an active site without displacing existing services. Similarly, the Santa Clara Valley Transportation Authority (VTA) is exploring affordable housing options at Tamien Station, utilizing a lease for transit property to increase housing capacity without displacing station users (VTA, 2023).

Opportunities for public-private partnerships (PPPs)

Governments can collaborate with private developers to combine public, discounted land with private sector expertise and capital. The most commonly used tool is the Request for Proposal (RFP) process, through which a city seeks proposals and selects a developer that can deliver the strongest mix of affordability, design quality, and community benefits (Andrea, 2003). These partnerships provide access to other funding sources such as Low-Income Housing Tax Credits (LIHTC), while long-term affordability is often secured through deed restrictions or community land trusts (Garcia, 2023).

By blending public oversight with capital and expertise from the private development sector, these relationships can enable municipalities to increase the supply of affordable housing while protecting community interests.

Government as a "bellwether" in incentivizing developers

By pursuing successful projects on public land, cities can lead by example and illustrate to private developers that affordable housing is a priority. Successful public land developments can demonstrate that projects are financially and logistically viable in high-cost markets, encouraging private sector participation in affordable housing initiatives. By this process, public land development is not only a tool for increasing housing supply but a platform for leadership.

Despite the promising strategy of using public land for affordable housing development, there are limitations. A primary challenge is community pushback: NIMBY activists rejecting higher density or affordability remains a commonality across the Bay Area. In Northern Sunnyvale, community scrutiny has led to delays in the Taj Mahal Fresh Market affordable housing redevelopment, which was previously an aging retail space (Cannestra, 2025). In Palo Alto, the proposed 231 Grant Avenue teacher housing project sparked opposition from neighbors concerned with density and parking (Martin, 2021). Another issue is the revenue potential for cities. If the land were sold at fair market value, cities could generate tens of millions of dollars in revenue to address other priorities, such as infrastructure or pensions. Allocating these parcels for below-market-rate housing means foregoing that revenue. Yet another issue is the permanent commitment that accompanies dedicating civic land for housing. Once a parcel is designated for housing, it becomes difficult to repurpose it for schools, parks, or other public functions. These

challenges highlight the need to balance immediate housing with long-term fiscal and planning objectives, while acknowledging public land as a viable resource - though not the ideal remedy.

Case Study: Los Altos

Los Altos' RHNA Allocation

State Housing Element Law, established in 1969, requires all local regions (cities and counties) to implement plans to meet their fair share of regional housing needs. The California Department of Housing and Community Development (HCD) enforces a requirement for each local government to execute plans that address the housing supply for everyone in its jurisdiction. The HCD goes through a vigorous process with each region's "Council of Governments" (COG) to determine the housing need across various income categories. The COG can then plan and develop an allocation methodology that becomes its "Regional Housing Need Allocation Plan" (RHNA Plan).

The RHNA target for the 6th cycle, 2023-2031, assigned for the City of Los Altos is 1,958 new housing units (Association of Bay Area Governments, 2025):

- Very low income (0-50% of AMI): 501 units
- Low income (50-80% of AMI): 288 units
- Moderate income (80-120% of AMI): 326 units
- Above moderate income (>120% of AMI): 843 units

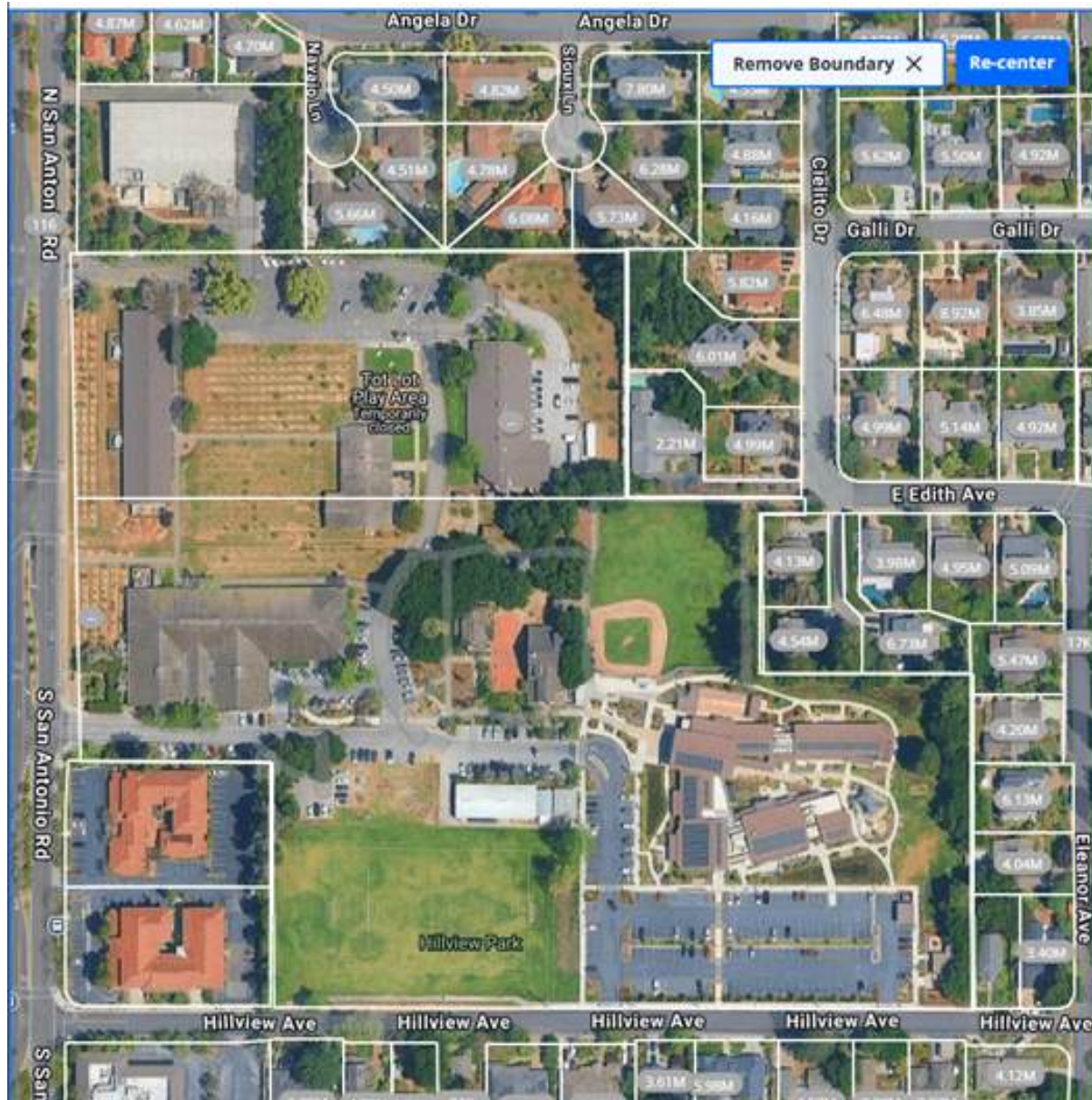
The most recent housing dashboard update (December 2024), which details the construction and permitting activities for various categories, showed a significant lag in the progress, especially in the "Very Low Income" level (Silicon Valley At Home, 2025):

Income Level	RHNA Target	Permits Issued	Progress
Very Low	501	12	2.4%
Low	288	101	35.1%
Moderate	326	116	35.6%
Above Moderate	843	280	33.2%
Overall	1,983	509	~26%

Analysis of Potential City-owned spaces

Repurposing underutilized city-owned spaces provides a viable option for housing development in suburban cities, which typically have lower housing densities. The preliminary analysis focuses on the City of Los Altos' city government and city library area, which assumes reconstructing the current single-story city government office and library to a multi-story mixed-use (residential and government office or library) building.

The City of Los Altos does not publish an exact total figure for the land acreage that the city government occupies. However, various online tools are available to help identify the city government building(s) and the boundary of the lot that the city government occupies. In the current analysis, the measurement of “available space” includes the existing building and parking lots. Areas that are for parks or sporting events are excluded.





Buildable footprint is translated from the lot size, and is affected by a number of factors—local zoning regulations, setback rules, and lot coverage (the maximum percentage of a lot that can be covered by impervious surfaces). This is referred to as Floor Area Ratio (FAR). In this analysis, an estimate of 25% as the FAR is applied to determine the size of residential square footage, and it is believed that projects that are 100% affordable housing spearheaded by the city government will have a more favorable FAR.

Lot size for the Los Altos City government and public library = 605,772 sq ft

Buildable residential area = 605,772 x 25% (FAR) = 151,443 sq ft

Assuming 50% of this residential area will be contributed back to the city as government office space or a library, the buildable residential area designated for the residential units is 151,443 sq ft x 50% = 75,722 sq ft.

A quick estimate for this buildable residential area yields a reasonable number of housing units; however, the unit mix matrix will ultimately be determined by the demographics of potential tenants, economic conditions, and regulatory requirements.

Unit Type	Average Size	Buildable Area	Approx Unit
Studio	400	75,722	189
1BR + 1BA	700	75,722	108
1BR + 2BA	1000	75,722	75

Analysis of other Bay Area Cities along the Peninsula

Applying similar calculations, the data for a few selected cities around the Bay are tabulated below:

City	City Government Lot Size (sq ft)	Buildable Area (after FAR applied)	1-bedroom Equivalent	RHNA Requirement	Progress %
Menlo Park	591,100	73,888	105	2,946	35.70%
Santa Clara	555,226	69,403	99	11,632	8.70%
Fremont	512,799	64,100	91	12,897	“modest”
Newark	321,017	40,127	57	1,874	4.50%
San Carlos	155,767	19,471	27	2,735	1%
Redwood City	157,966	19,746	28	4,588	18%
Hayward	268,815	33,602	48	4,624	“lag behind”
San Leandro	147,654	18,457	26	N/A	<4%
Belmont	132,994	16,624	23	1,765	<2%
San Bruno	142,553	17,819	25	3,165	<5%

Conclusion

Given the scarcity of land resources and the high cost of housing development around the Bay Area, it is crucial for all interested stakeholders, including developers and city governments, to consider options other than private projects to increase the total supply of housing in the Bay Area. Redeveloping land that is currently being occupied by city governments and public libraries can make a meaningful contribution to California’s RHNA mandate. This may serve as a replicable model for other communities to follow.

Appendix

Methodology

To identify city governments and their public libraries that are dated and single-story, Google Maps Street View is primarily used, along with physical visits to verify potential sites. Cities like Mountain View, Palo Alto, and San Jose are excluded because they already have multi-story office buildings and are unlikely to adopt the proposed approach.

Limitations

This analysis is subject to a number of limitations, including:

- Errors in data quality: estimates were made using online tools regarding the areas occupied by the city government and public libraries.
- Zoning conditions: zoning conditions of city government offices and public libraries may not be ideal for mixed-use housing developments.

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A Review of Mechanism-Based Immunotherapies and Precision Medicine for IBD

By Sohum Ratnaparkhi

Abstract

Inflammatory bowel disease (IBD), encompassing Crohn's disease and ulcerative colitis (UC), comprises chronic, relapsing immune-mediated disorders which have considerable global health impact. Its pathogenesis occurs from a mix of genetic susceptibility, immune dysregulation, microbial imbalance, and environmental triggers. While clinical management currently centers on broad immunosuppression due to our insufficient understanding of these factors, emerging mechanism-based and targeted therapies do have the potential for further precision disease control. Breakthroughs in biologics targeting TNF, integrins, and interleukins, along with oral small molecules such as JAK and S1P modulators, have broadened treatment options, though safety and biomarker-guided selection remain challenges. Cellular and engineered T-cell therapies, including regulatory T cells and mesenchymal stem cells, aim to restore long-term immune tolerance, especially in refractory phenotypes.

Microbiome-modulating therapies like standardized fecal transplants and next-generation probiotics aim to recalibrate mucosal immunity, alongside spatial transcriptomics and multi-omics profiling. This review evaluates immunotherapies from an integrated, mechanism-based perspective, as pathway-selective and cell-targeted strategies may better address disease heterogeneity and better personalized outcomes. Despite progress, mucosal healing is not achieved for many, and heterogeneous responses, immunogenicity, and subclinical inflammation still remain significant challenges. Next-generation trafficking blockers, barrier-repair approaches, and checkpoint modulators are advancing but require standardized endpoints and safety data. AI-assisted diagnostics, noninvasive monitoring, and direct tissue sampling promise accelerated personalization toward true disease modification. The future of IBD care depends on merging immunologic, microbial, and technological innovations to deliver viable precision outcomes.

Intro

Inflammatory Bowel Disease (IBD) is a group of chronic immune disorders that target the gastrointestinal tract, with ulcerative colitis (UC) and Crohn's disease as the primary clinical diseases. These illnesses remain a considerable issue in current medicine, consistently linked to significant morbidity and reductions in patient quality of life across all age groups (Muzammil et al. 1). UC is characterized by a prolonged inflammation in the colonic mucosa, usually originating at the rectum and extending proximally. Crohn's disease causes patchy, transmural inflammation that can affect any part of the gastrointestinal tract, but most frequently the terminal ileum and colon. Though UC is limited to the innermost layer of the colon, Crohn's disease is capable of extending to deeper layers of the bowel wall, causing complications such as stricture, fistula, and abscess.

The etiopathogenesis of IBD includes genetic predisposition, dysfunctional immune responses, changes in the gut microbiome, and environmental stimuli (Imhann et al. 3). Both UC and Crohn's disease result from an aberrant immune response to intestinal microbiota in a genetically susceptible host and result in inflammation cycles, tissue damage, and dysfunctional mucosal healing (Aldars-García et al. 1). Although research has made sizable progress, the exact causes of IBD are not completely understood yet, and neither of the conditions are currently curable.

Besides gastrointestinal symptoms like diarrhea, abdominal pain, rectal bleeding, urgency, anemia and weight loss, IBD is also associated with extraintestinal conditions involving the skin, eyes, joints, and hepatobiliary system (Muzammil et al. 6). Both UC and Crohn's disease patients have a greater risk of colorectal cancer and can require surgical intervention for complications (Selinger et al. 2). The increasing occurrence of IBD and its unpredictable and vague presentation warrant greater-precision diagnostics and personalized therapeutic treatments, which continue to remain the aim of current translational innovation and research.

Biologic Therapies

Biologic agents are foundational aspects of managing IBD, proving essential in controlling inflammation and preventing disease progression. The major biologic classes include anti-tumor necrosis factor (anti-TNF) agents, anti-integrins, and anti-interleukin-12/23 (anti-IL-12/23) antibodies (Dave and Loftus 30). Anti-TNF therapies, such as infliximab, adalimumab, and certolizumab pegol, first transformed IBD treatment by specifically inhibiting TNF- α , a cytokine that promotes gut inflammation and tissue damage (Souza et al. 7). They have demonstrated high efficacy for inducing and sustaining remission in both Crohn's disease and UC, including the fistulizing phenotypes as well.

The next wave of biologics attempts to solve these issues by expanding precision targeting. Anti-integrin agents, such as vedolizumab, selectively block $\alpha 4\beta 7$ integrin, a molecule that directs lymphocyte trafficking to the gut (Park and Jeen 5). Since vedolizumab is mostly confined to the gastrointestinal tract, it offers a more robust anti-inflammatory action with a reduced risk of side effects like systemic immunosuppression and other infections. Anti-IL-12/23 antibodies like ustekinumab block shared subunits of IL-12 and IL-23, disrupting pathways that drive T-helper cell differentiation and chronic intestinal inflammation (Aggeletopoulou et al. 3). These agents have shown high clinical remission rates in Crohn's disease and are increasingly used for UC, often after anti-TNFs fail or are not tolerated. The latest IL-23p19-specific agents like risankizumab aim for an even more precise level of immune modulation, shown by high efficacy in phase 3 trial data particularly in refractory Crohn's disease and UC (D'Haens et al. 1).

Due to the high cost and limited access to biologics, biosimilars (nearly identical copies of the original drugs) have been increasingly important. Biosimilars to infliximab and adalimumab have exhibited equivalent efficacy and safety in large, real-world IBD patient populations (Huguet et al. 3). Wider adoption is helping to reduce treatment costs and broaden access, though challenges still exist in switching between products, and regulatory limits.

Despite these advances, important limitations remain. For example, immunogenicity, when the patient's immune system mounts a response against the biologic, is still a key factor behind secondary loss of response, especially for anti-TNF agents (Velikova et al. 1). Head-to-head trial data comparing the effectiveness and safety of newer biologics compared to more established therapies are still limited. In addition, standardized biomarkers to predict or monitor biologic response are still lacking, as currently, clinicians must rely on visible symptoms, bloodwork, stool tests for fecal calprotectin, or endoscopies (Iskandar et al. 12). Direct mucosal and GALT sampling, when paired with spatial transcriptomics, is a developing approach that offers a path toward more individualized biologic selection and monitoring. It may help in matching the right biologic to the right patient earlier, keep patients on the most effective option for longer, and avoid unnecessary exposure to drugs for non-responders. Integrating these therapies with spatial molecular monitoring, expanding access to biosimilars, and continuing to conduct comparative trials are essential to effectively and smartly treating patients with IBD.

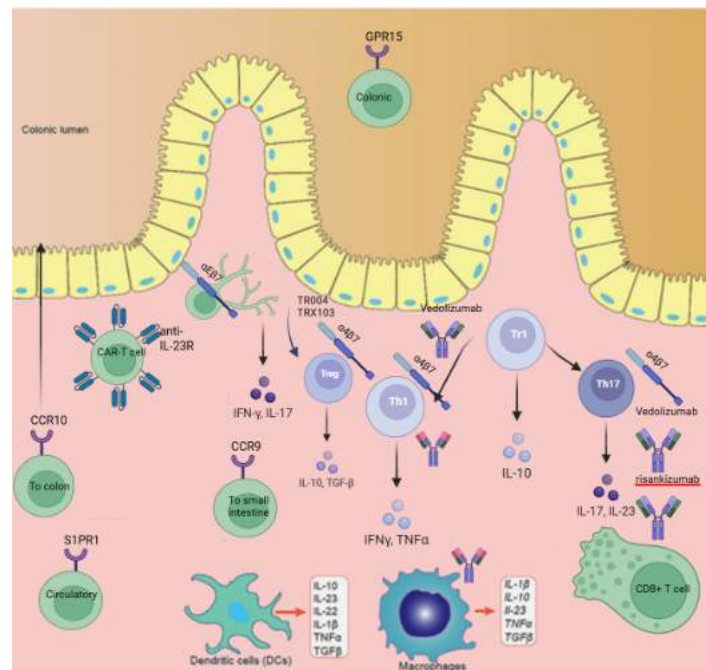


Fig 1: Mechanisms of immunotherapeutic intervention in IBD demonstrate regulation of T cell trafficking receptors (CCR9, CCR10, S1PR1, $\alpha E\beta 7$, $\alpha 4\beta 7$, GPR15) and cytokine signaling (IL-10, IL-17, IFN- γ , TNF α , TGF- β , etc.) to modulate effector and regulatory T cell subsets.

Small Molecule Inhibitors

Small molecule inhibitors have become an increasingly important oral therapeutic option in the treatment of inflammatory bowel disease, offering the ability to target intracellular pathways that cause inflammation. The primary classes with approved or late-stage development include Janus kinase (JAK) inhibitors tofacitinib and upadacitinib, sphingosine-1-phosphate (S1P) receptor modulators ozanimod and etrasimod, and other candidates in development such as TYK2 and PDE4 inhibitors (Fansiwala and Chauk 7). These drugs are mechanistically different

from biologics in that they act intracellularly to inhibit signaling cascades essential for immune cell activation and trafficking, thus inhibiting inflammatory cytokine production and immune cell migration to the gut mucosa. JAK inhibitors target members of the JAK family that participate in cytokine receptor signaling, modulating networks like interleukins and interferons. In contrast, S1P modulators regulate lymphocyte release from lymphoid tissues, reducing the influx of activated immune cells to the intestine. Oral administration and their rapid onset of action demonstrate a high potential for patients looking to avoid injectables (Herrera-deGuise et al. 10).

Due to the risks of infections, thrombosis, and other abnormalities associated with JAK inhibitors, safety profiles are also a necessary consideration for small molecule inhibitors. Although the short-term efficacy of tofacitinib and upadacitinib in inducing and maintaining remission in UC has been established, long-term safety monitoring and real-world experience may reveal other risks. S1P modulators have shown promising efficacy and might have a more selective modulatory action with fewer side effects, though careful monitoring for cardiac and infectious side effects is still important (Akram et al. 7). Comparisons between the drug classes are limited by the lack of larger head-to-head trials, and heterogeneity in patients and disease phenotypes makes generalizations about their efficacy and safety even less definitive. In clinical practice, treatment selection often depends on an individual patient's previous therapy history, overall health, lifestyle preferences, and tolerance for future monitoring (Herrera-deGuise et al. 8).

A key unmet need in small molecule therapy is the lack of reliable, easy-to-use biomarkers to predict who will have an optimal response and personalize dosage over time. Currently, clinicians rely mostly on trial-and-error strategies with dose titration based on symptom control and inflammatory markers, which might not fully capture the immunological processes.

Therapies combining small molecules with biologics or microbiome-modulating therapies are still under investigation to enhance efficacy and reduce loss of response (Cai et al. 1). This will require prospective clinical trials with real-time biomarkers and integration of spatial and functional immune monitoring in the GALT, and moving from peripheral blood or stool-based biomarkers to direct tissue-based samples. Filling these gaps is essential to maximize the potential of small molecule inhibitors as effective and personalized therapies for moderate to severe IBD.

Cellular and Engineered T Cell Therapies

Cell-based therapies are a means of resetting the IBD-affected immune system by restoring tolerance and rebalancing T cell responses that are not regulated in chronic inflammation. One of the more studied options is the infusion of regulatory T cells (Tregs), which can be harvested from the patient and expanded ex vivo, or increasingly, engineered for more stability and better targeted to gut tissues. Evidence from pilot studies, such as the TRIBUTE trial led by King's College London, shows that adoptive Treg infusions can directly reduce effector T cell activation and inflammation within the GALT, with expanded Tregs

displaying greater suppressive function than those found in peripheral blood (Hassan et al. 1). Furthermore, companies like Tr1X are now advancing trials of engineered Tr1 Treg therapies, leveraging robust IL-10 production for enhanced local immunosuppression (Johnson). Meanwhile, mesenchymal stem cell therapies, supported by multiple cohorts including Barnhoorn, are already available for treatment of perianal Crohn's disease, achieving durable fistula closure and improved disease control in recent studies (Włodarczyk et al. 11).

Engineered T cell therapies, like CAR-T and TCR-T approaches, are now being repurposed from cancer to gut immunity (Cui et al. 2). T cells are now being designed to specifically recognize and neutralize pathogenic, disease-causing clones or deliver local anti-inflammatory signals within the GALT. However, the translation from oncology presents different challenges. These engineered cells must traffic and survive within the complex intestinal environment, avoid off-target effects, and be produced at scalable cost and speed for chronic disease (Neurath et al. 4). Risks of cytokine release syndrome, aberrant immune response, or long-term engraftment must be addressed through next-generation therapy controls and digital monitoring.

Sequential direct sampling from GALT using endoscopic biopsies, spatial immune profiling, and functional single-cell assays can be applied to prove whether infused or engineered cells successfully engraft and reset immune response at the correct locations. Progress will also depend on establishing more objective, tissue-based metrics, like evidence of local tolerance restoration or reduction in effector cell infiltration, to move beyond early concept models and toward therapies that can truly provide safe, resistant, and reproducible remission for patients with IBD.

The potential for combining cellular therapies with other methods like biologics, small molecules, or microbiome interventions could further increase their efficacy and durability. The development of off-the-shelf engineered T cell products, as well as advances in targeted delivery and in-vivo imaging, could make them a feasible option outside of research centers.

T Cell Subset	Key Markers	Role in IBD Progression	Role in T Cell Therapies
Th1 (CD4+)	IFN- γ , T-bet, CXCR3, TNF- α	Drive cell-mediated inflammation; predominant in Crohn's	Target for suppression; Treg and anti-cytokine therapies
Th17 (CD4+)	IL-17, IL-22, ROR γ t	Promote neutrophil recruitment; chronic inflammation in IBD	Targeted by anti-IL-23/IL-17 therapies
Treg (CD4+, Regulatory)	FOXP3, CD25, IL-10, TGF- β	Suppress inflammation, maintain tolerance; often reduced or dysfunctional in IBD	Expanded or engineered for adoptive cell therapy
Tr1 (Type 1 Regulatory)	IL-10, no FOXP3, CD49b, LAG-3	Suppress effector immunity, especially via IL-10	Source for cell therapy, especially in experimental trials
CD8+ T cells (Tc1, Tc17)	IFN- γ or IL-17, Granzyme B, CD8	Cytotoxic; can worsen tissue injury in active IBD	Potentially engineered (TCR-T) to downregulate pathology
Tissue-Resident Memory (Trm)	CD69, CD103, CD49a, variable cytokines	Expanded in active IBD (esp. Crohn's); may cause relapse/flaring	Being profiled for precision cell targeting
CAR-T / TCR-T (Engineered)	CAR or TCR constructs (tumor or inflammation-specific)	Designed for cytotoxic precision or immune modulation	Experimental therapy, target or correct key pathogenic clones
Central/ Effector Memory T cells	CD45RO, CCR7 (central), CD62L	Memory compartments feed recurrence, chronicity	Being studied as infusion source, or targeted for depletion

Table 1: Key T cell subsets in IBD: markers, roles in IBD progression and T cell therapy

Microbiome-Modulating Strategies

The gut microbiome is closely tied to both the initiation and persistence of mucosal inflammation. Fecal microbiota transplantation (FMT) has demonstrated that thorough restoration of microbial communities can induce clinical remission in UC. But results have been mixed, as the risk of relapse and endurance of benefit remain significant concerns (Chen et al. 17). To address this variability, the field is moving toward standardized, more defined microbial consortia and engineered next-generation probiotics that can reproducibly transform the local immune environment. These designed microbial therapeutics aim to increase production of

anti-inflammatory compounds, such as short-chain fatty acids, or to better calibrate antigen presentation in GALT, modulating the function of mucosal T and B cells (Nishida et al. 2).

Recent multi-omics and spatial transcriptomics studies, including those from the ENDO-Omics IBD consortium and groups like Ilott et al., have demonstrated that mapping microbial communities and their interactions with local immune pathways in patient biopsies can identify gene signatures correlating with treatment response and disease activity (Su et al. 12). These studies have shown success in defining distinct subgroups of IBD patients who are more likely to benefit from microbiome-targeted therapies, mostly due to their unique microbial and immune profiles, while others show minimal or no improvement, often because their baseline microbiota and mucosal immune state are less responsive to intervention. This form of precision profiling is essential, as not all patients receive benefit, and targeted therapy can spare individuals unnecessary treatments while optimizing remission rates for likely responders (Nicholson). The integration of dietary, prebiotic, and synbiotic strategies into these omics frameworks is now highlighting which metabolic and immunological effects are achievable, rather than assuming universal efficacy across diverse IBD populations.

Practical challenges include maintaining consistency from batch to batch, risk of pathogen transfer, and receiving regulatory approval as "living drugs." However, the recent FDA clearance of certain live microbiome products demonstrates clinical readiness for greater clinical use (Sood et al. 5). The long-term goal is even more personalized microbiome modulation in real-time, based on immunological phenotyping and demonstrated changes in GALT function, with long-term remission with minimal toxicity.

There is still much to be understood about the role of the microbiome in modulating gut immunity. Approaches that pair defined microbial therapies with established immunosuppressive, cellular, or dietary interventions are also gaining traction (Hitch et al. 6). Ongoing trials are testing whether such multi-modal approaches can sustain control of inflammation and induce greater mucosal healing or tolerance, with the hope of decreasing reliance on drugs with systemic side effects.

Immune Trafficking Modulation

Selective modulation of immune cell trafficking has become an increasingly important strategy for limiting gut inflammation while preserving immune strength. Vedolizumab is the gold standard of $\alpha 4\beta 7$ integrin blockers, specifically blocking lymphocyte homing to the gut by blocking the MAdCAM-1 ligand, leading to symptom control and mucosal healing with a lower risk of systemic infections than earlier biologics (Veny et al. 2). S1P receptor modulators, like ozanimod and etrasimod, sequester lymphocytes in lymph nodes to prevent them from accumulating in the intestine. Together, these therapies have shown high efficacy, particularly for UC, but are now being tested in larger, real-world IBD patient pools (Rath et al. 13). Despite this progress, many patients do not achieve full or durable remission, partly because immune cell trafficking involves multiple, redundant pathways that allow pathogenic cells to bypass blockade. Next-generation trafficking blockers, such as oral integrin inhibitors (AJM-300),

anti-MAdCAM-1 antibodies (ontamalimab), and CCR9 antagonists, are being developed to target distinct gut-homing receptors and overlapping pathways to address these gaps (Caballero Mateos et al. 5). These agents aim to improve response rates, extend therapeutic durability, and better control extraintestinal symptoms, while reducing systemic immunosuppression, which is essential to handle the heterogeneity and complexity of IBD in heterogeneous patient pools.

The development of next-generation trafficking blockers is rapidly advancing, targeting even more specific molecules like CCR9, CCR10, and GPR15, which regulate lymphocyte migration to distinct gut regions (Wiendl et al. 3). Another approach can target the gut-liver pathway (for primary sclerosing cholangitis) and the gut-brain-immune axis, as they have shown potential for positively impacting mood, fatigue, and cognitive symptoms commonly experienced by IBD patients (Wang et al. 6).

However, as the human immune system has adapted various defensive migration pathways, intercepting one mechanism can result in other routes being upregulated (Nish and Medzhitov 7). Therefore, success will require not only new drug development but also greater resolution, biomarker evaluation, utilizing direct mucosal biopsy, spatial cell profiling, and possibly in vivo tracking of immune cell migration. Effective long-term use of trafficking modulators depends on monitoring whether pathway inhibition truly results in local immune inactivity in GALT, rather than any other alternative off-target or suppressive mechanisms.

Further research should explore and address patient stratification, by developing tools to identify patients with a greater likelihood of benefiting from trafficking inhibitors while minimizing risk of adverse effects (Xue et al. 8). As monitoring technologies advance, real-time tracking of trafficking and immune cells in GALT could allow for adaptive therapy, optimizing patient benefit while closely monitoring loss of effect or safety concerns.

Mucosal Healing and Barrier Restoration

Thorough mucosal healing has become increasingly important for IBD remission. Such cleaning has led to reduced rates of disease relapse, surgery, and even colorectal cancer (Travis 1). However, only a fraction of current patients achieve actual, stable mucosal healing, and microscopic disease can persist even after visible symptoms disappear (Otte et al. 3).

Strengthening the gut barrier are new avenues of current research. Promising prospects include R-spondin and Wnt pathway agonists, which stimulate stem cell renewal inside crypts, as well as bioengineered epithelial cell implants for repairing damaged tissue (Harnack et al. 1). Surrozen, a leading company in this space, has demonstrated that their clinical candidate SZN-1326, a Wnt mimetic targeting FZD5/8 and LRP6 receptors, robustly repairs colon epithelium and reduces inflammation in preclinical colitis models without causing epithelial hyperplasia, a key safety concern (Xie et al. 12). However, while these therapies show potential, additional clinical testing and refinement is underway to optimize their efficacy and guarantee long-term safety, particularly to avoid unwanted proliferation or oncogenic risks.

Modern technologies are revolutionizing the measurement metrics of such healing. In addition to traditional colonoscopy, clinicians now use AI-assisted imaging and spatial transcriptomic biopsies to precisely measure recovery and immune rebalancing (Sedano et al. 6).

However, many inconsistencies in outcome definitions, molecular biomarkers, and trial endpoints still remain across early studies (Vieujean et al. 10). There remains a need for shared criteria across diseases for mucosal/epithelial healing that can support clinical practice and future research into these barrier-restoring therapeutics.

Checkpoint Inhibitors

Checkpoint pathways, which are routinely used in oncology, are currently being closely researched for their role in gut immune tolerance and activation. Immune checkpoints such as PD-1, PD-L1, CTLA-4, LAG-3, and TIGIT act as molecular "brakes," subduing resident T cells and preventing unchecked inflammation in healthy mucosa (Triantafillidis and Apostolos 1). In IBD, checkpoint dysregulation may cause persistent inflammation, and it may be discovered that checkpoint agonists, instead of inhibitors, could restore regulatory pathways or rejuvenate exhausted T cells in the gut (Baroz et al. 7).

Safe clinical translation of these pathways would necessitate newer generation delivery systems. Localized dosing, like oral antibody fragments or hydrogel implants, precisely targets the intestines while also decreasing possibility for adverse events (Zhang et al. 1). There is also research exploring pairing checkpoint therapies with microbiome modulations or existing small molecules to achieve more specific regulation of GALT immunity (Hwang et al. 5).

However, risks such as flares or other unexpected immune adverse effects persist (Abu-Sbeih et al. 5). There remains a great need for tissue-resident exhaustion markers, spatial immune profiling, and more precise clinical models before moving to larger trials. Checkpoint-based therapies could pave the way for much more precisely and safely achieving immune balance for IBD.

Multi-Omics

Advances in multi-omics (integrating genomics, epigenomics, transcriptomics, proteomics, and metabolomics) are revolutionizing our understanding and treatment of IBD. By understanding the complete biological causes of disease, researchers can now identify precise patient endotypes, rather than vague labels of Crohn's disease or UC, allowing for far more personalized therapy options (Wang et al. 21).

Artificial intelligence, combined with multi-omics data, has already begun to aid early clinical tools. Machine learning models integrate molecular data with traditional lab markers and imaging to predict who will best respond to specific therapies, anticipate relapses, or optimize dosing (Qiu et al. 6). However, most data from existing models comes from readily accessible blood or stool samples, which may not provide an accurate representation of the complex immunopathology of IBD within GALT.

Recent research has shown great promise for multi-omics approaches that directly sample gut-associated lymphoid tissue through endoscopic biopsies, as well as utilizing spatial transcriptomics. The aim of these strategies is to identify molecular signatures and immune cell changes that predict response or toxicity to emerging therapies, such as JAK inhibitors and S1P modulators, eventually being able to fully individualize treatment strategies (Baldan-Martin et al. 2). Direct tissue sampling allows for a more accurate mapping of therapeutic impact, which could aid in identifying early responders and patients at higher risk of adverse effects (Atreya and Neurath 9).

Serum metabolomics, like tryptophan metabolites, and detailed immune cell profiling are additional multi-omics approaches being researched. Though they each demonstrate potential for stratifying patients or effectively monitoring treatment, most require greater validation to move from research into standard clinical practice (Lai et al. 11).

Combined with novel real-time monitoring technologies, like ingestible sensors and wearable biosensors, these therapies could transform care into being much more proactive, with a more precise and continuous molecular monitoring of disease and tissue response. Long-term, this approach has the potential to completely revolutionize clinical trial and practice, offering a dynamic and much more precisely monitored treatment to improve safety and overall patient outcomes.

Conclusion

Recent advances across the various IBD therapies, from biologics and small molecule inhibitors to engineered cell therapies and microbiome modulation, have significantly expanded the potential for achieving more durable, and efficient remission of Crohn's disease and UC. Although current approaches can effectively control most inflammation, a substantial proportion of patients still fail to achieve consistent mucosal healing or experience significant side effects (Parigi et al. 10). Persistent heterogeneity in therapeutic response and the sheer complexity of IBD pathogenesis underscore the need for personalized therapies that account for genetic, immunologic, and environmental factors (Fiocchi & Iliopoulos 3).

Technological advancements, including multi-omics profiling and real-time in vivo immune monitoring, are transforming our ability to stratify patients and match therapies to particular disease mechanisms. Innovation in regenerative medicine, more advanced cell therapies, and targeted trafficking blockers may yield greater control over intestinal inflammation, but also restoration of immune tolerance and sustainable mucosal repair (Okamoto et al. 1). However, challenges of safety, cost, delivery, and standardized results still persist.

The future of IBD treatment will require a greater application of precision diagnostics and evidence-based adoption of next generation modalities (Caballero Mateos et al. 11). As collaborative research enhances our understanding of the microbiome's mechanisms, epithelial barrier, immune cell networks, and genetics, real-time and individualized care for IBD can become a safe reality, improving results and quality of life for patients worldwide.

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Evaluation of A Volatile Layer in Mercury By Viransh Hingarh

(1) Introduction

Mercury has a striking feature of volatiles on its surface, a topic discussed thoroughly by scientists after the discovery of them and development of the idea after the MESSENGER era.

This study develops an idea of a volatile layer on Mercury. While suggested before, it hasn't been brought to much light in existing theories. We fit our model to explain current trends, and underlining key processes that could shape our understanding of volatiles on the surface of Mercury.

(2) Chronological Model

(2.1) Introduction

4.5 Ga, Mercury accreted from highly reduced enstatite chondrite material. Differentiation brought a metallic core and pyroxenite dominated mantle (Boujibar et al. 2025). On the mantle was the global HMO, and an early, Mercurian Atmosphere was born.

(2.2) Early Atmospheric Conditions

The early atmosphere was thought to form from outgassing from the Hermean Global Magma Ocean. The lifetime of this state of the mantle was only short lived, as it underwent complete solidification of the magma ocean within 20 Myr since the formation of the solar system. This resulted in a short lived lifetime of the atmosphere, until it collapsed due to mantle cooling and SiO₂ opacity.

Modeling efforts by Jäggi et al. (2021) using a combined modeling strategy of the following models:

1. SPIDER (Bower et al. 2018, 2019, 2021)
2. VapoRock
3. VULCAN (Tsai et al. 2017, 2021)
4. DISHOOM (Oza et al. 2019 ; Gebek & Oza 2020)
5. The Exospheric Monte Carlo (E-MC) Model (Wurz & Lammer 2003; Vorburger et al. 2015; Gamborino et al. 2019)

The thermal evolution of the magma ocean is modeled from 2400 K to 1500 K mantle temperatures, prior to a surface graphite lid forming at 1500 K (Vander Kaaden & McCubbin 2015). The model predicts that the magma ocean takes 3400 yr for this cooling trajectory.

Atmospheric pressures reach 5 bar at 2000K surface temperature. These high pressures are credited to the contribution of gaseous CO and H, as the metal bearing species (Na, K, SiO, MgO, CaO, AlO, FeO) contribute around 0.1 bar. Below the homopause, the CO and H take up 27 and 60 vol% respectively.

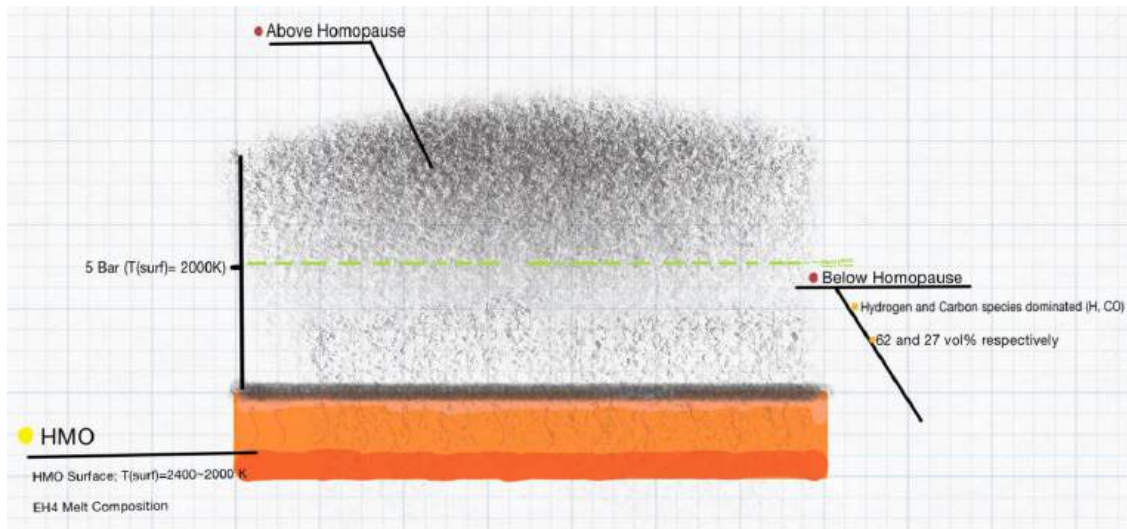


Figure 1: Diagram of an Early Mercurian Atmosphere (Data derived from Jäggi et al 2021)

At surface temperatures of 2000K, Na and K are the most dominant metallic species. At the surface their hydroxide forms (NaOH, KOH) are abundant, with minor trace species of sodium hydride (NaH) but they dissociate in the atmosphere.

Atmospheric Species	vol% (Below Homopause)	Additional Information
H	60	Both H and CO species gave the atmosphere its high pressure (5 bar)
CO	27	Both H and CO species gave the atmosphere its high pressure (5 bar)
Other (Na, K, SiO, MgO, CaO, AlO, FeO)	13	Na and K were the most dominant species at surface temperatures of 2000 K. All of these species combined only contributed to 0.1 bar to the early atmosphere

Table 1: Model of atmospheric components and their contribution below the homopause. Data was derived from a combined-modeling approach by Jäggi et al. (2021)

(2.3) Condensation Trajectories

H-bearing species and gasses would be swept away and lost from the atmosphere due to processes like photo-evaporation, diffusion, photo-ionization, plasma heating, and jeans escape (Jäggi et al. 2021). C-bearing gaseous species (CO) would partly condense onto a surface graphite lid, as they are highly refractory elements.

Oxides such as SiO, MgO, CaO, AlO, and FeO are also rather high refractory compounds, and would be condensed onto the surface graphite layer in the finishing stages of

mantle solidification. MgO and SiO would condense into olivine or forsterite, turning into signature minerals we observe on the surface.

Na, K, and other trace volatiles (sulfides and salts, though not entirely confirmed) would condense to the surface after surface temperatures cool down below a threshold of 1500K.

Atmospheric Species	Condensation Trajectories (Collapse of The Atmosphere)
H- and C- bearing species	Would be swept away due to solar wind, photo-evaporation, diffusion, photo-ionization, plasma heating, and jean escape. C- bearing species will condense partly to the graphite surface as they are highly refract
Oxides (SiO, MgO, CaO, AlO, and FeO)	Highly refractory. These will condense onto the graphite lid before surface temperatures cool down to 1500 K. MgO and SiO compounds will form forsterite, olivine, and enstatite.
Na and K	These species (and other trace volatiles) will condense below surface threshold of 1500 K on the graphites

Table 2: Model of atmospheric condensation trajectories. Atmospheric species data was derived from a combined-modeling approach by Jäggi et al. (2021)

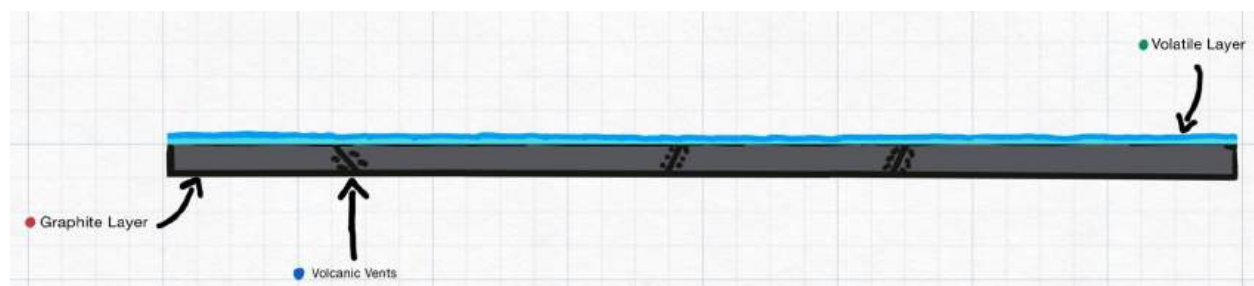


Figure 2: Diagram of a layer of condensed volatiles on top of a graphite layer. Green: volatile layer made of condensed Mg, SiO, Na, K, etc. (illustrated in blue shades) Red: graphite surface lid. Blue: volcanic vents.

(2.4) Plains Formation

After condensation, there would be a thin, yet prominent layer of minerals (many containing volatiles) upon the primary graphite layer, also rich in carbon, another volatile and a candidate material for hollow's formation.

At around 4.0 Ga, high pressure and depth magma melts rose to form the magnesium-rich Intercrater plains. The condensed volatiles on the graphite layer became a part of this melt when it embedded itself in the upper region of the secondary crust (the Intercrater plains). This would form a uniform, nearly global upper volatile layer.

(2.5) Structural Changes to The Volatile Layer

Approximately 3.9~3.8 Ga, The Late Heavy Bombardment occurred. This was a period of time where the inner solar system was under heavy asteroid impacts. Mercury's surface was also affected by it, with millions of crater impacts scarring the surface. These impacts also caused major changes in the structure of the uniform, upper layer of volatiles. Large impacts caused excavation of the surface, exposing local areas of the volatile layer, causing them to go under outgassing and hollowing, eventually forming the first generation of hollows. These impacts also caused surrounding areas to get buried under newly formed regolith. Throughout the LHB, local areas of the volatile layer would be exposed and others would be buried deeper into the crust. This would make the volatile layer uneven.

Silicate-rich Smooth Plains formation from shallower, lower pressure melts (3.8~3.5 Ga) and later volcanism would bury the uneven layer. Making the volatile layer in these areas hardly accessible unless excavated by large asteroids. Late stage volcanism and tectonics could also affect the depth and structure of this volatile layer.

Present day micrometeorite impacts and asteroid belt impactor populations induces regolith mixing, further embedding the volatile layer deeper into the crust

(3) Contribution to Surface Features

(3.1) Glacial Lobes/Features

Rodriguez et al.,(2023) provides an analysis of glacier-like features and its indication of volatile-rich layers (VRLs) extending several km in depth. Detailed observation of the Raditladi basin revealed these glacial-structures, characterized with lobated fronts and a convex upward surface topography, indicative of viscous, glacier-like melt behavior. This feature would have formed from the exposure of the volatile layer from an impact, and the flow of the exposed part of the VRL would then melt to form the glacier-like lobes.

When an impact occurs, a heat anomaly under the peak ring causes a partially melted region. The instability in the peak ring ridges would cause ductile flow, forming apron-like lobes of glacial-like melt.

The preservation of these lobes could be possible due to the formation of repository lags able to significantly inhibit devolatilization.

Sodium compounds such as NaCl (halite) are key candidates for the volatiles that cause this glacial-like flow. Halite is also subject to ductile deformation at 200 degrees celsius, and has a significant drop of viscosity after 400 degrees celsius.

They suggest that the VRLs are deposits situated and formed after major volcanism and plains formation due to geometric data revealing an expanse of VRLs over the North Pole, superposing craters and other, older terrain. Our model contradicts this, as according to early atmospheric models (Jaggi et al 2021), the atmosphere collapses prior to major plains formation, meaning that the condensation of volatiles from that atmosphere forming the VRLs is older than major plains formation. Furthermore, while it may seem that the features are younger than the

surrounding terrain, the volatile layer doesn't have to necessarily be younger than the surrounding terrain. The exposure of the volatile layer after its formation due to impact cratering or other processes would cause the formation of the glacial-like flows on the surface, similar to how hollows are younger than the craters that induce their formation.

(3.2) Hollows

The following is the analysis from a recent work on hollows formation and chemical evolution by Emran and Stack (2025)

Sulfides like CaS and MgS are key volatile candidates for hollows formation in LRM excavated regions, due the absorption feature at 0.63 μm in the hollow spectra. Other regions could also concentrate and expose chloride species.

During high-energy impact events on Mercury, calcium and magnesium sourced from a near-surface volatile-rich layer can react with sulfur originating from deeper low-reflectance material (LRM) to form CaS and MgS in situ. The impact generates extreme localized heating and pressure, which both mixes the previously separate reservoirs and provides the thermal energy necessary for sulfide formation. Under these transient high-temperature conditions, sulfur can chemically combine with the exposed Ca^{2+} and Mg^{2+} , crystallizing as CaS and MgS as the system rapidly cools. This process is spatially localized, occurring primarily in impact melts or ejecta deposits, and relies on the intimate mixing of volatile-layer cations with sulfide-bearing material from the deeper crust.

The formation of hollows on Mercury commences with the thermal desorption or decomposition of these newly formed sulfides in surface or shallow subsurface materials, concomitantly with the sublimation of concentrated volatiles. This process initiates the active stage, where hollow growth is sustained primarily by the devolatilization of sulfur, accompanied by additional carbon loss through sputtering induced by space weathering and photon bombardment. As these volatile losses diminish, the hollows transition into a waning stage, leaving behind lag deposits composed predominantly of non-volatile silicate minerals and some incompletely devolatilized volatile-bearing species. These lags function as a resistant covering that suppresses further deepening of the hollows. Over time, spectral data indicate an increasing silicate contribution, reflecting the decline of sulfide content, which ultimately restricts continued hollow development.

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Ethnocentrism and Media Framing: Hierarchical Representation of Foreign Nationals in South Korea

By Junhee Yu

Abstract

Across the globe, multiculturalism has become a defining social trend, with many countries embracing ethnic diversity and immigrant integration as central to their national identity. South Korea, however, has exhibited a comparatively limited transition toward multiculturalism. Despite rapid increases in immigration since the 1990s, Korea's strong ethnonationalism and homogeneity prevent multiculturalism in Korea. To analyze the unique pattern of racism in Korea, attributed to Korean homogeneity, this study investigated how such xenophobia is reflected in South Korea media represented immigrants. I analyzed news coverage from January 2024 to May 2025 concerning five countries: the United States, Japan, China, Thailand, and Vietnam. Keyword frequency, word cloud visualization, and sentiment analysis were conducted to examine framing patterns and emotional tone. Word frequency depicts differences across nations: the U.S. has balanced sentiment, shaped by political alliance; Japan is portrayed ambivalently, shaped by historical rivalry and fear; China is strongly associated with violent crime, generating disgust and fear; while Thailand and Vietnam are depicted in reductive terms associated with drug-related crime and illegal residency, thus reinforcing negative stereotypes. These results demonstrate that xenophobia in Korean media operates hierarchically in ways shaped by Korea's social, political, historical, and geographical connections to each country. Understanding these differentiated patterns in relation to Korea's historical and geopolitical context helps clarify the mechanisms through which racism and xenophobia are reproduced. Thus, this study provides a foundation for future studies on multicultural integration.

1.Introduction

Recent global data shows significant increases in international migration in South Korea. In 2020, approximately 3.6% of the global population were international migrants, representing the highest proportion registered in the last thirty years. Following the worldwide flow, South Korea has experienced significant immigrant growth since the 1990s. More than half a million foreigners resided in South Korea by 2006, with international migrant workers accounting for the majority (Kim, 2009). The largest groups include Chinese of Korean descent (27.5% or 532,000), Vietnamese (12.8% or 247,000), Chinese (11.4% or 221,000), and Thais (9.9% or 191,000) (Yoon, 2024). Furthermore, Vietnamese showed the highest growth rate at 18.1%, followed by Thais at 16.8% and Chinese at 8.5% (Yoon, 2024).

Unlike other countries characterized by long-standing ethnic diversity, South Korea shows its unique form of racism due to homogeneous ethnic composition. South Korea has traditionally been "known for its cultural uniqueness and ethnic homogeneity"(Shen, 2017) and has long "viewed itself as an ethnically homogenous society"(Park, 2014). This self-perception as "one of the most racially and culturally homogeneous nation-states" (Yuk,

2014) became deeply embedded in Korean identity. The homogeneity is a dominant characteristic of Korean society that makes its racism distinctive.

The unique South Korea's form of racism appears to be hierarchical, reflecting diverse ethnic and national identities. Korean racism operates through "a hierarchy of different ethnic/national migrant groups established through a logic of class and conferred cultural values, determined largely by conceptions about the economic status of the migrants' country of origin" (Yu, 2022). This creates a racialized framing where "the intersection of class and nationality in everyday narratives generates the racialized framing of migrant 'others'" (Yu, 2022). In this framework, the intersection of nationality and class generates a racialized differentiation of "migrant others." Importantly, Korean racism is shaped by what has been described as an aspiration for whiteness and abjection of blackness (Lee, 2024), a dynamic that privileges Western/white migrants while marginalizing non-Western migrants, particularly African American and Southeast Asian groups.

In the context of racism, the media plays a crucial role in both reflecting it and reinforcing it. Media framing theory shows selective representation in media emphasizing certain aspects of immigrants while downplaying others. Research demonstrates that "the way in which news about immigration is presented and its repetition influence the creation of stereotypes and prejudices". Since the media shapes public perception of immigrants through selective representation of information, analyzing its portrayals of immigrants is crucial for understanding the operation of xenophobia and racism in South Korea.

Although previous research has examined Korea's unique form of racism and its ethnonationalist foundations, fewer studies and analysis of how the racism differs by the nationality of immigrants. Research demonstrates that migrants' "diverging experience of integration in Korea" is significantly influenced by their national background (Yu, 2022). However, detailed comparative studies examining specific differences between nationalities remain limited, representing a critical gap in understanding how Korean racism operates differently across various migrant communities. This paper hypothesizes that the Korean media reflects on its racism on immigrants differing by their nationality. Specifically, the media selectively overreports information based on their nationality – ultimately reinforcing prejudice against particular groups such as Thai and Vietnamese migrants. By analyzing how Korea's unique mechanism of racism operates through media, this research aims to bring the hierarchical racism of Korea into the surface. By understanding racism not merely as an abstract concept but as a set of concrete practices that produce various prejudices toward different national groups, Korea can advance toward a more multicultural and embracing society.

2. Methods

2.1 data collection

To investigate how each nation is represented in Korea, we collected Korean news data through the News Archive Big KINDS (www.kinds.or.kr) provided by the Korea Press

Foundation, a comprehensive news analysis platform managed by the Korea Press Foundation. Big KINDS was selected because it provides access to a wide range of Korean news outlets, offering systematic coverage across major national newspapers and broadcasting companies.

The analysis focused on five countries that consistently appeared with the highest volume of coverage in the dataset: the United States, Japan, China, Thailand, and Vietnam. These countries were selected not only due to their quantitative prominence in Korean news reporting but also because they reflect diverse geopolitical and cultural relationships with Korea. Articles were retrieved using each country's name as the primary search keyword, restricted to publications between January 2024 and May 2025. This timeframe was chosen to capture the most recent patterns in media representation and sentiment. Duplicated articles and irrelevant results were manually screened and excluded, yielding a cleaned dataset for analysis.

2.2 Data preprocessing

Before analysis, all collected text data underwent a series of preprocessing steps. Articles were first converted into plain text format and cleaned by removing punctuation, numerical symbols, advertisements, and non-informative tokens. Common stopwords (e.g., grammatical particles and auxiliary words) were filtered out to ensure meaningful keyword extraction. The dataset was then tokenized using Textom, a Korean big data analysis platform capable of accurately segmenting words in Korean text, which is morphologically complex. This step allowed the extraction of base morphemes (e.g., nouns, verbs, adjectives) to improve accuracy in subsequent frequency analysis.

2.3 Word cloud

Word cloud and sentiment analysis were conducted to visualize the frequency and prominence of keywords in Korean new coverage. The collected data was preprocessed by removing stopwords, punctuation, and irrelevant symbols, and it was tokenized using textcom—Korean big data analysis platform—to accurately segment Korean words. Term frequencies were calculated and the resulting values were used to visualize a word cloud as shown Figures 1-5 . This method allowed for an intuitive representation of the keywords most strongly associated with each country in the dataset.

2.4 Sentiment analysis

To complement keyword frequency analysis, a sentiment analysis was conducted to evaluate the emotional tone of articles. Sentiment classification was carried out using the Korean Sentiment Lexicon integrated in Textom, which categorizes words into major sentiment categories such as positive (e.g., interest, admiration) and negative (e.g., fear, disgust, anger). Each article was assigned sentiment scores based on the aggregated presence of sentiment-related terms, enabling both quantitative comparison and qualitative interpretation of the prevailing emotions toward each nation. The results allowed us to identify distinct emotional profiles—for example, whether a country was associated primarily with fear, disgust, or interest.

3. Result

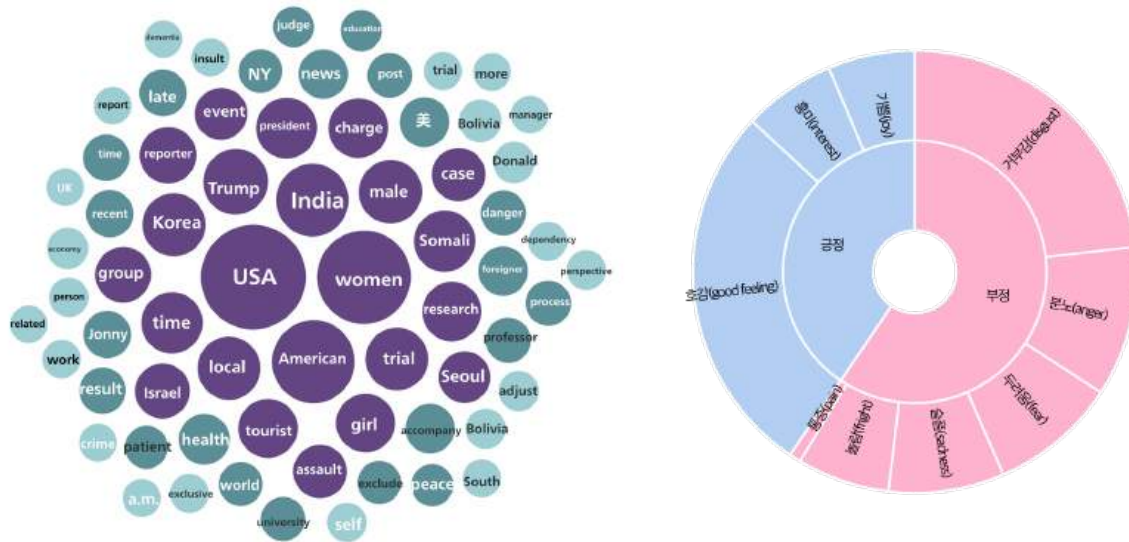


Figure 1. Word cloud and sentiment analysis for U.S in Korea media

3.1 U.S.

Keywords from news concerning the United States exhibit diversity, making it challenging to identify a single dominant theme. The observed keywords cover a broad spectrum of topics, including 'international affairs,' 'judges,' 'dementia,' 'education,' 'insults,' and anomalies in New York news trails.' The dataset is largely composed of keywords reflecting major global news topics. In the case of sentimental analysis, sentiments associated with United States

3.1.1. U.S. Bubble Chart

Rather than focusing on a single negative incident, keywords associated with the US exhibit a broad spectrum of issues. Keywords such as 'perception,' 'reporting,' 'department head for unusual behavior,' 'occurrence,' 'presidential allegations,' 'reporter,' 'Trump,' 'United Kingdom,' 'male,' 'India,' 'risk,' 'recent,' 'Korea,' 'Somali,' 'vassal state,' 'economy,' 'foreigner's perspective,' 'group,' 'female,' 'United States,' 'people,' 'progress,' 'research,' 'time,' 'Johnny,' 'professor,' 'local American,' 'trial,' 'Seoul,' 'adjust,' 'result,' 'Israel,' 'girl,' 'tourist,' 'accompany,' 'Bolivia,' 'criminal,' 'defect,' 'health,' 'assault,' 'badge,' 'peace,' 'south,' 'morning,' 'exclusive,' 'century,' 'university,' 'self,' 'related,' and 'work' are challenging to generalize in single theme, as shown in figure 1. The production of news in South Korea related to the United States includes various categories, such as politics, society, culture, and international relations.

3.1.2 U.S. sentimental analysis

The sentimental analysis of the United States showed relatively balanced emotions, since negative emotions appeared slightly more than positive emotions. Among 237 words, there were

141 negative words and 96 positive words. The approximation percentage of positive emotion and negative emotion was 41% and 59%. In case of negative emotions, “disgust” appeared to be the highest proportion, at 23.21% of all terms. “Anger” was the second highest negative emotion, accounting for 10.97% of all terms. “Good feeling” was the most frequent positive emotion, standing as 65 out of 96 positive words. Also it accounted as 27.43% of all terms, ranking it as the highest portion among total sentiments. Following “good feeling”, “interest” accounted for 6.75% and “joy” for 6.33%, indicating similar proportions.

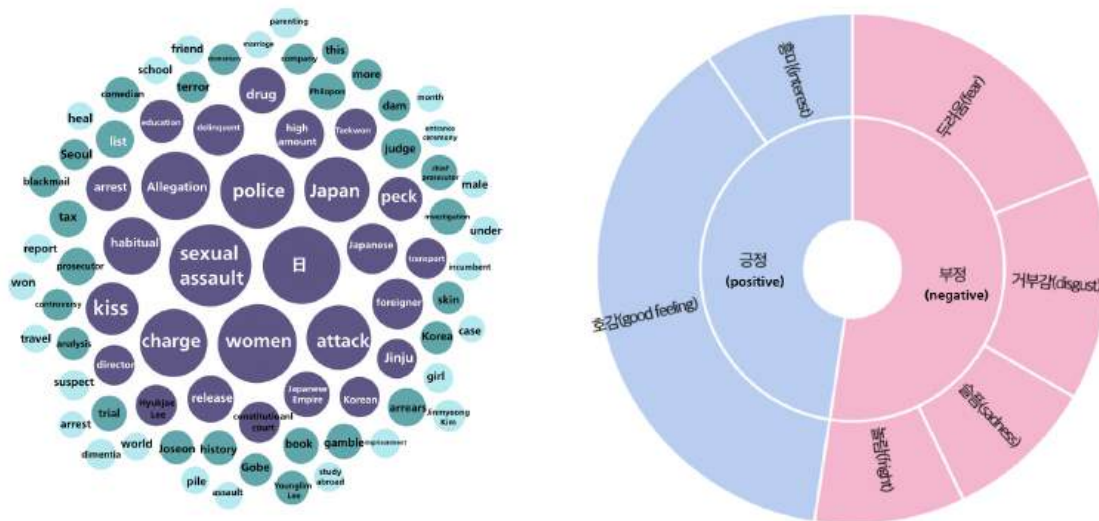


Figure 2. Word cloud and sentiment analysis for Japan in Korea media

3.2. Japan

Keywords related to Japan includes some negative terms related to sexual harassment, but most of the terms appears to be neutral. Also the observed sentiments showed the most balanced ratio of positive emotions and negative emotions among all five countries. The various news keywords and balanced sentiments exhibit the complexity of Japan to South Korea, not limiting it to mere creator of incidents but relating to their historical issues and diverse issues.

3.2.1 Japan Bubble Chart

News keywords related to Japan includes some terms associated with sexual harassment such as “sexual harassment” and “police”, but most of the keywords appear to be neutral. Various terms such as 'friend's marriage,' 'school,' 'terrorism,' 'drugs,' 'treatment,' 'education,' 'entrance ceremony,' 'judge,' 'Seoul,' 'inspection point,' 'male,' 'threat,' 'arrest,' 'indictment,' 'Japan,' 'police,' 'kiss,' 'investigation,' 'tax,' 'sexual harassment,' 'yen,' 'foreigner,' 'skin,' and 'controversy' are observed. Additionally, keywords such as ‘Joshun,’ ‘Japanese colonial period,’ ‘history’ exhibit the historical relationship between Korea and Japan.

3.2.2 Japan sentimental analysis

The sentimental analysis of Japan revealed relatively balanced positive and negative emotions. Out of 21 total terms, 10 were positive and 11 were negative, resulting in a ratio of 47.62% positive to 52.38% negative. Among negative emotions, "fear" was the most prevalent, accounting for 4 out of 11 negative terms (19.05% of all terms). This is a notable contrast to other countries where "disgust" is often the top negative emotion. "Disgust" was the second-highest negative emotion, at 14.29%. On the positive side, "good feeling" was the most common emotion, with 8 out of 10 positive terms (38.1% of all terms), followed by "interest" and "joy," which each accounted for 9.52% of the total terms.

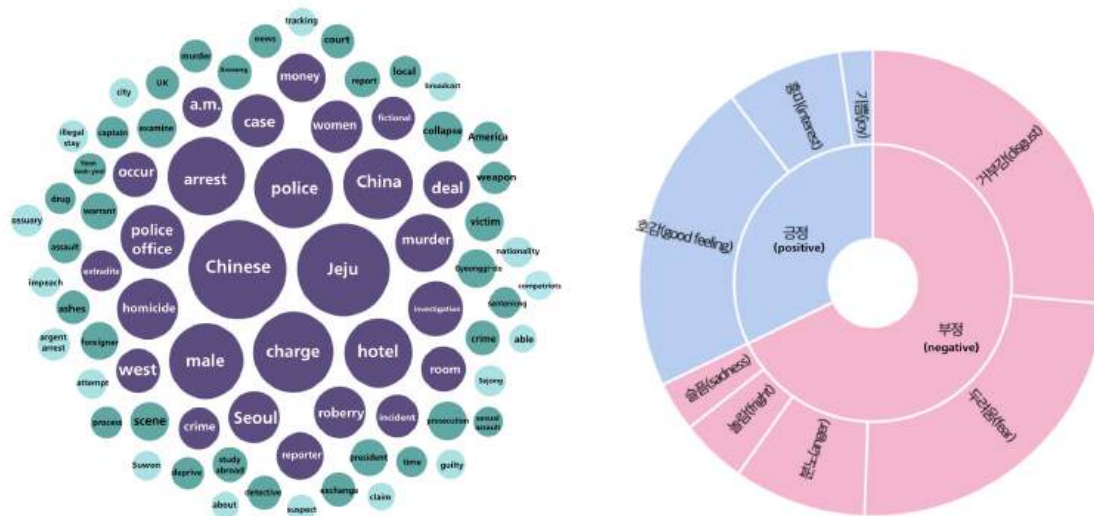


Figure 3. Word cloud and sentiment analysis for Japan in Korea media

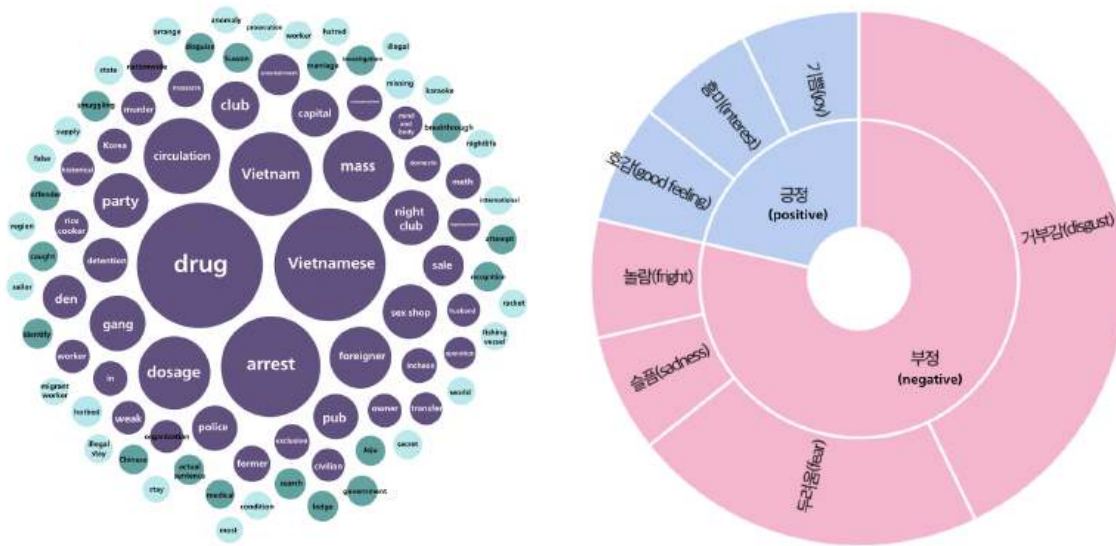
3.3 China

News keywords for China are mostly related to crime, especially violent crimes like murder. The observed keywords show a narrow range of spectrum, which are predominantly characterized by crime reports. The sentimental analysis also shows a high proportion of negative emotions.

3.3.1 China Bubble chart

The bubble chart for China is dominated by crime related keywords, especially violent crimes such as murder and robbery. 'allegation,' 'police,' 'detention,' 'murder,' 'investigation,' 'robbery,' are the most dominant keywords. A wide range of crime related keywords also appear, such as 'warrant,' 'assault,' 'remand,' 'detective,' and 'suspect.' The keywords reveal that most of the news coverage about China heavily focuses on crime reports.

3.3.2 China Sentiment Analysis



3.4. Thailand and Vietnam

News keywords for both Thailand and Vietnam are mostly related to drug-related crimes. Bubble charts for both countries are dominated by crime related terms, especially about drugs. Sentimental analysis consistently shows a high proportion of negative emotions, exhibiting a high ratio of disgust among all emotions in both countries.

3.4.1. Thailand Bubble chart

The bubble chart for Thailand is dominated by keywords associated with drug related crime, with central terms including 'drugs,' 'police,' 'allegation,' and 'detention.' Other keywords, such as 'gambling,' 'warrant,' 'arrest,' and 'mass,' also largely focused on criminal activity. Minor keywords such as 'illegal stay,' 'nationality,' 'immigration law,' and 'residence' also showed topics related to illegal immigration.

3.4.2. Vietnam Bubble chart

Similarly, Vietnam's bubble chart is primarily composed of keywords related to violent crime. The most prominent keywords, 'drugs,' 'Vietnamese person,' 'arrest,' 'drug use,' and 'trafficking,' are all linked to drug offenses. Other terms like 'party,' 'detention,' 'police,' and 'illegal stay' also focus on crime reporting, with very few neutral keywords present. Minor keywords related to illegal immigration, such as 'illegal stay' and 'residence', are also shown.

3.4.3. Thailand Sentiment Analysis

The sentiment analysis for Thailand reveals a highly negative emotional profile. Out of 53 total terms, 42 were negative (79%) and only 11 were positive (21%). 'Disgust' was overwhelmingly the most frequent negative emotion, with 26 terms (49% of all terms). 'Fear' was

the second most frequent, with 10 terms(18.87%). Among the positive terms, 'good feeling' was the highest, with 9 terms (17%). 'Interest' and 'joy' each appeared once (1.89%).

3.4.4. Vietnam Sentiment Analysis

Vietnam also showed a very high proportion of negative emotions. Out of 14 total terms, 11 were negative (79%) and only 3 were positive (21%). 'Disgust' was the most frequent negative emotion, with 6 terms (42.86%). 'Fear' was the second most frequent, with 3 terms(21%). The three positive terms were equally distributed among 'good feeling,' 'interest,' and 'joy,' each with one term (7.14%).

4. Discussion

4.1 Summary of findings and interpretation

The analysis of news keywords and sentiment reveals a multi-layered pattern of xenophobia in Korean media, shaped by a country's perceived historical, cultural, and geographical proximity of each country to Korea. Xenophobia is not uniformly applied to all foreign nationals but operates on a differentiated and hierarchical basis, reflecting a Korean's perception of different nations.

In Korean news media, the U.S. is portrayed as a complex and multifaceted subject of various world issues. News keywords cover a broad range of topics, and sentiment analysis shows a balanced ratio of positive emotions like good feeling and interest alongside negative ones. This suggests that the US is not reductive or uniformly hostile framed by Korean news media. The U.S. is not subject to a simplistic, negative framing, considering historical alliance and geopolitical proximity of two nations, and global prominence of the U.S., resulting in predominantly neutral emotional recognition. The xenophobia toward the U.S. is not a generalized aversion or crime report, reflecting a wide range of world issues.

Japan placed a distinctive position in Korean media coverage with its balanced ratio of positive and negative sentiments. Unlike other nations, the primary negative emotion associated with Japan is 'fear,' rather than 'disgust.' This distinct emotional profile reflects a complex relationship shaped by geographical proximity and a shared history, including colonial rule. The sentiments suggest that Korean media's coverage of Japan is not a simple dislike or neutrality, rather it is a complex mix of geological proximity and shared history. Further, the dominant negative emotion of 'fear' suggests the undercurrent of caution or apprehension, which indicates that Korean's perception of Japan is neither simple hostility nor neutrality, but a layered mix of familiarity, rivalry, and vigilance.

In Korean media, China is framed as a source of violent crime, with prevalent keywords such as "drugs" and "murder". Sentiment analysis shows that "disgust and fear are almost equally dominant. This balanced presence of both disgust and fear indicates that China's negative perceptions are not solely rooted in criminality but also in broader geopolitical concerns . This

nuanced framing reflects a deeper societal anxiety, positioning China as a complex and multilayered source of concern with deeper societal anxieties and a complex sense of unease.

In contrast, news coverage of Vietnam and Thailand is heavily focused on violent crime, with prominent keywords like 'drugs,' 'murder,' and 'illegal stay'. The sentiment analysis for these countries reveals overwhelmingly negative emotions, particularly disgust and fear. This suggests that due to a perceived lack of deep historical and cultural engagement with Korea, these nations are often viewed through a simplified, more reductive manner, for example, primarily sources of criminal threat. This may contribute to a perception of them as 'criminal' or 'dangerous,' which reinforces a simplified and stigmatizing narrative.

Overall, the differentiated emotional and framing across nations by Korean news media demonstrates that Korean media's xenophobia is context-based and shaped by complicated interplays of history, culture, and geopolitical considerations. This might suggest that these factors — proximity, historical and geographical context — shape the emotional coverage, giving rise to distinct patterns of hostility or neutrality toward specific nations.

4.2 The differential application of xenophobia in Korean Media

4.2.1 Xenophobia in Korea

(a) main cause

The primary driver of xenophobia in South Korea is deeply rooted ethnocentrism stemming from feelings of cultural superiority. Research indicates that South Korean society's tendentious actions toward other countries result from looking down on other cultures, particularly following Korea's transformation from a colonized nation to a developed economy. This ethnocentric worldview manifests as a lack of cultural sensitivity toward other countries, even when controversial incidents arise (Mulyaman, D., & Ismail, A. (2021)

Korean ethnic nationalism —promoted historically as “one language, one history, one ethnicity”—has reinforced assimilationist policies rather than multiculturalism and still influences contemporary attitudes. (Shin, 2013; Choi 2010)

Economic concerns further exacerbate xenophobic attitudes. South Koreans hold prejudice against North Korean refugees primarily because they believe supporting these refugees wastes government resources (Okuyama, 2022). Research demonstrates that income predicts anti-refugee beliefs better than partisanship or ideology. Broader anti-immigrant sentiments are also linked to economic insecurity, inequality, and sociotropic concerns about national resources. The group threat model explains how social capital and socioeconomic status relate to anti-foreigner sentiments at both structural and individual levels (Lee et al, 2024). Economic insecurity, unequal material distribution, and sociotropic economic concerns all significantly predict support for restrictive immigration policies (Kim 2021). Threat perception serves as a crucial mediator in understanding intergroup prejudice and anxiety toward refugees and minorities (Yuk and Shin, 2024). However, contact theory provides a counterbalance—research shows that higher percentages of multicultural households in

neighborhoods are associated with more favorable attitudes toward multicultural society (Kim 2016)

(b) Toward other Asian groups

Korean Chinese workers experience significant ethnic discrimination despite sharing physical similarities and ethnic heritage with native-born Koreans (Lee et al, 2024). Survey experiments reveal that South Koreans show different levels of support for immigration policies depending on group identity: highest support for North Korean defectors (co-ethnic group), lower support for Korean Chinese (semi-coethnic group), and lowest for Indonesian guest-workers (non-coethnic group) (Ha et al, 2016). Interestingly, individuals exposed to Korean Chinese cues experience higher levels of cultural and social threat than those exposed to Indonesian cues, while South Koreans experience higher economic threat from North Korean defectors than from Korean Chinese and Indonesians (Ha et al, 2016). In addition, Thai and Vietnamese migrants represent two of the largest Southeast Asian communities in Korea, primarily consisting of marriage migrants and migrant workers (Lee and Park, 2023; Park, 2022)

4.2.2 Linguistic and Cultural Marginalization

Southeast Asian marriage migrants, including Thai and Vietnamese women, face systematic linguistic discrimination in multiple contexts. They are stigmatized for their linguistic and cultural backgrounds, positioned as incompetent second-language speakers due to regional dialects and lack of sociolinguistic competence (Park, 2017). In workplace settings, they experience marginalization based on their language abilities and are pressured to strictly adhere to traditional Korean linguistic and cultural norms within three-generation households (Park, 2017).

4.2.3 Stereotyping and Social Perceptions

Thai marriage migrant women are commonly perceived as "less-educated, passive, financially dependent, and helpless victims of domestic violence from a third-world country" who migrated through matchmaking agencies to marry older Korean farmers or factory workers (Lee & Park, 2023). Despite government efforts to raise awareness about multicultural families, public prejudice against Thai marriage migrants remains largely unchanged (Lee & Park, 2023). Vietnamese women face similar stereotyping, with their marriages often viewed through the lens of economic necessity rather than genuine partnership (Park, 2022; Atabas, 2023).

4.2.4 Workplace and Community Discrimination

Both Thai and Vietnamese migrants experience racial discrimination in broader community settings based on their language and ethnicity (Park, 2017). They face limited meaningful contact and intercultural communication with Koreans across various social contexts, including households, workplaces, and wider communities (Park, 2022). The discrimination extends to negative stereotyping about their class, gender, and race (Park, 2017)].

4.3 Framing effect by media

The media plays a crucial role in shaping public perceptions of immigrants, often reinforcing prejudices through various psychological and communication mechanisms. Media framing theory shows that selective presentation of information in media emphasizes certain aspects of immigration while downplaying others and shapes public perceptions (Park, 2022).

4.3.1 Media Framing Theory and Immigrant Perceptions

Media framing plays a critical role in shaping public perceptions of immigrants by selective presentation of information. A Spanish media analysis revealed that immigration is predominantly framed "as an irregular event, causing feelings of rejection and xenophobia" (Tirado-Espín et al., 2021). The framing process involves both explicit discursive mechanisms and sourcing strategies that construct immigration as a problem and position immigrants as "others" in media discourse (Miloni, D. et al., 2015). Different frames produce distinct effects: economic frames highlight costs and benefits, while security frames emphasize threats and dangers (Cheregi, 2018). Research demonstrates that "the way in which news about immigration is presented and its repetition influence the creation of stereotypes and prejudices" (Tirado-Espín et al., 2021). Experimental evidence shows that exposure to negative immigration frames increases support for punitive policies through sequential mediation of anger, contempt, and outgroup derogation (Kim, et al., 2018)

4.3.2 Hierarchical representation of immigrants in Korean media

South Korea's transformation from an ethnically homogeneous society to a multicultural one has been accompanied by distinct patterns in how news media represents different immigrant groups. Since the early 1990s, the influx of labor migrants, marriage migrants, and refugees has challenged Korea's traditional self-image as a mono-ethnic nation (Park, 2014; Kim, 2009). This shift has created a complex media landscape where representations of immigrants vary dramatically based on their countries of origin, revealing underlying biases and hierarchical thinking about race, ethnicity, and national value.

Korean media constructs a clear hierarchy in immigrant representation based on national origin and perceived economic value. Research analyzing Korean television dramas from 2005-2012 found that non-Korean characters were categorized into four distinct groups: "adoration" (primarily white males from USA/Europe in professional careers), "sympathy" (Southeast Asians and blacks as underprivileged workers), "proximity" (Japanese and Chinese), and "other" (Ju and Noh, 2013). This categorization reflects broader societal attitudes about which immigrants are considered valuable versus problematic.

The hierarchical nature extends beyond entertainment media into news coverage. Analysis of major Korean newspapers from 1990-2008 revealed that immigrants are constructed differently based on their perceived economic utility and cultural proximity to Korean society (Park, 2014). Western immigrants, particularly those from developed countries, are framed as contributing to

Korea's globalization and modernization efforts, while those from developing nations are often portrayed as requiring assistance or posing integration challenges.

a. Positive Framing

Korean media often portrays Western immigrants, particularly white men, in highly favorable terms. Television programming depicts them as "exemplary cosmopolitan citizens" characterized by attractive appearances and professional careers such as doctors or lawyers (Ahn, 2022; Park, 2014). This "adoration" category reflects Korea's aspirational relationship with Western modernity and global standards. The concept of "Para-Koreans" has emerged to describe how Western foreigners are represented as ideal immigrants who express affection toward Korea while maintaining their foreign identity (Eydum, 2022). These individuals are portrayed as intelligent, high-status, likeable, and cosmopolitan — embodying the type of diversity Korea desires (Bakker, 2023). However, this representation comes with paradoxical expectations: they must assimilate enough to appreciate Korean culture but not so much as to lose their "foreign" distinctiveness that defines their media value.

b. Economic and Cultural Capital

Western immigrants benefit from association with Korea's modernization and development goals. Korean Americans, for instance, are viewed as valuable contributors who bring foreign expertise and capital, receiving privileges under policies like the Overseas Koreans Act (Lee, 2010). This dynamic illustrates a hierarchical model of belonging in which social inclusion is influenced by perceived economic and cultural capital.

c. Negative Stereotyping

In contrast, immigrants from Southeast Asia, Central Asia, and Africa face systematic negative representation in Korean media. They are predominantly portrayed in the "sympathy" category - as underprivileged groups consisting mainly of females and low-paid workers (Ju and Noh, 2013). This framing positions them as objects of pity rather than as contributing members of society. Marriage migrants, particularly women from Southeast Asia, are recurrently framed as "social issues" or potential sources of social tension, reflecting the persistence of male-centered production norms and audience preferences (Lee, 2010). The production-level analysis shows that a "Korean-male-centered" perspective and desire for mass audiences contribute to this othering process.

d. Assimilation Pressures

Unlike Western immigrants who are often celebrated for their foreignness, Southeast Asian and African immigrants face intense pressure to assimilate completely into Korean society. They are expected to adopt Korean cultural norms, language, and social behaviors while receiving little recognition for their own cultural contributions (Bakker, 2023). This contrast

highlights how cultural hierarchies shape media expectations about which forms of difference are celebrated and which are problematized.

e. Proximity and Ambivalence

Chinese and Japanese immigrants occupy a complex middle position in Korean media representation. Japanese immigrants are often portrayed as "rich people that are highly competent" and able to cooperate easily with Koreans, reflecting historical economic relationships and cultural similarities (Ju and Noh, 2013). However, this positive representation coexists with underlying historical tensions. Chinese immigrants, particularly ethnic Koreans from China (Joseonjok), face discriminatory treatment despite their ethnic connection to Korea. While Korean Americans receive preferential treatment, Joseonjok are "treated as foreign migrant workers in low-skilled sectors" and prevented from receiving benefits available to other overseas Koreans (Lee, 2010). This differential treatment reveals how economic class intersects with ethnicity in determining media representation.

5. Conclusion

This study demonstrates that xenophobia in Korean media is not applied uniformly across immigrant groups but instead varies by nationality, historical context, and perceived cultural capital. The comparative analysis of media portrayals of the United States, Japan, China, Thailand, and Vietnam reveals that immigrants are framed through distinct emotional and thematic lenses : favorable or multifaceted in the case of Western countries, ambivalent in relation to neighboring nations, and predominantly negative for Southeast Asian groups. Such differentiated framing underscores the hierarchical structure through which South Korean media constructs immigrant identities and reflects broader societal attitudes toward multiculturalism. Grounded in theories of media framing and intergroup relations, this research highlights the role of press as a critical site in which national identity and xenophobia are reproduced. These results contribute to a deeper understanding of the mechanisms of racism and xenophobia in South Korea, offering a foundation for future studies of immigrant representation and its implications for multicultural integration.

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Detecting Early-Onset Alzheimer's from Spontaneous Speech Using an LLM

By Yasin Makhtiev

Abstract

Early diagnosis of Alzheimer's disease (AD) from spoken speech has become a primary challenge in neurocognitive computing. While previous systems typically utilized either linguistic or acoustic characteristics in mono modality, this paper presents a multimodal large language model (LLM) that fuses both modalities at the embedding level to enhance diagnostic accuracy and estimate MMSE score. Taking the ADReSS challenge corpus as a data source, speech portions underwent ASR and acoustic disfluencies, pause dynamics, and lexical complexity analysis. Textual embedding derived from a transformer-encoded embedding was aligned in time with acoustic feature representations obtained from a CNN-encoded audio embedding. It is shown that the multimodal model significantly outperformed monomodal text and audio baselines, obtaining accuracy and F1 score levels of 86.9% and 0.84 compared to text- and audio-only systems, which obtained levels of 82.0% and 78.0%, respectively. For MMSE regression, the model obtained a mean absolute error (MAE) value of 3.61, outperforming previous state-of-the-art methods like BERT+SVM (MAE = 4.56) and multimodal TF-IDF + MFCC (MAE = 7.56). Analysis of pausal and lexical content indicated that AD speakers contained $2.3\times$ more inter-sentence and $3.1\times$ more intra-sentence pauses, and contained a percentage of lexical diversity that was 19% lower compared to control. These are the first findings to substantiate that embedding-level concatenation of acoustic and textual characteristics retains information that complements the effects of cognitive deterioration, resulting in enhanced detection and MMSE score estimate. Apart from benchmark advances, this approach shows the promise of multimodal LLMs as clinical ancillary tools for early-stage AD screening and monitoring of cognitive function.

Introduction

Alzheimer's Disease (AD) is the most common form of Dementia, estimated to make up 60-70% of all cases worldwide [1]. In 2020, the total number of people living with Dementia was over 50 million [2]. This number is projected to reach over 80 million in 2030, and 152 million by 2050. Furthermore, despite its widespread prevalence, the actual number of those living with Dementia is predicted to be much higher, with an approximated 75% of cases remaining undiagnosed, largely due to the difficulty in detecting Early Onset Dementia (EOD); early symptoms arise in subtle manners, so the detection of Dementia occurs when the severity of the disease is nearing its apex. This issue is only exacerbated for low and middle income countries, where a lack of understanding about the disease limits public awareness, with the 75% figure reaching 90% [3]. Early detection of Dementia – and in this study, AD – is therefore critical, as it facilitates interventions and attempted treatments which are unlikely to succeed in advanced cases. Additionally, those who are diagnosed earlier tend to be more encouraged to participate in key clinical trials, and some studies show that their institutionalisation is delayed heavily,

providing more relief to both the care-givers and the affected person. Despite that, current diagnostic approaches tend to be expensive, and time-consuming; even in the United Kingdom, a developed country, those with suspected AD struggle to get a proper appointment, with the average wait time rising from 13 weeks in 2019, to 22 weeks by 2024 [4]. In light of these issues, over the last few years, a new concept has been brought up, using Artificial Intelligence as a tool which can notice patterns in speech to determine whether a person is likely to have AD or not. Language Learning Models (LLMs) are able to capture distinct textual and paralinguistic features which humans fail to catch consistently, despite them being directly linked to cognitive decline. LLMs can therefore not only present a new style of detection, but it can also make detecting AD faster, and cost little to nothing for the patient; if a software was developed that could be integrated into hospital environments, and potentially even phones — with the LLM achieving high diagnostic accuracy based on a sampled dataset — it could loosen the burden on doctors, lower the costs of the hospital, heavily reduce wait times for the people, and with some backing from a professional, be a decisive technique to deduce the existence of AD in a patient. This paper focuses on developing just that: choosing an unbiased, reliable dataset, training an LLM using that data, tweaking the characteristics of the LLM to perform at its most optimal condition, comparing it to other LLMs and methods, implementing it into an easy-to-integrate, open source software, and concluding whether the software is successful or not in its ability to detect AD.

Alzheimer's Disease and Its Effects on Speech

AD is a neurodegenerative disorder which targets older adults, with Early Onset Alzheimer's Disease (EOAD) also being for those below the age of 65. AD is the cause of 60-70% of Dementia cases, and symptoms are seen through a decline in memory, critical thinking, behaviour and cognition.

The progression of AD can be broken down into early, middle and late (alternatively, mild, moderate and severe respectively). Early stages include some difficulty in speech, and mild forgetfulness, whereas the late stages would show a loss of speech to a noticeable degree, as well as severe cognitive disability. This is to not be confused with early and late onset, which is connected to the age of the person who is experiencing AD (EOAD would pertain to anybody below 65, and Late Onset Alzheimer's Disease (LOAD) would be for those older than 65). Understanding the impact of AD also requires understanding the neurological causes of the symptoms, particularly how it can be visible in speech.

The speech degeneration visible in AD, and more specifically, EOAD, is due to the degeneration in the language focused brain sections. Moreover, the Broca's and Wernicke's areas, as well as the temporal-parietal junction, are affected, which leads to synaptic loss. Vocal symptoms can be seen with a slower rate of speech, longer or consistent pauses in speech, reduced pitch changes and abrupt hesitations. Textual symptoms can be seen in anomia (the inability or difficulty to retrieve words), substituting complex words with simpler ones, and

a reduced vocabulary in general. Additionally, coherence and narrative structure also begin to worsen, leading to disorganised speech.

Given that these linguistic and vocal impairments are measurable, researchers have explored computational methods to detect EOAD using spontaneous speech.

Previous Approaches to The Existing Problem

Traditional approaches to the detection of AD from spontaneous speech are mostly performed through Machine Learning (ML). Similar to LLMs, ML detection works through the analysis of primarily textual features with some vocal recognition as well. This includes vocabulary depth, the repetition of words, pause frequency and timings.

This is then followed by a classification through Random Forests, or Support Vector Machines. The data was usually extracted from the Cookie Theft picture description (seen in Fig.1) from the Boston Diagnostic Aphasia Exam (BDAE), where patients were requested to describe a complex scene. They were tested on the richness of their vocabulary, as well as syntactic complexity. Traditional ML models focusing on both types of data in spontaneous speech typically achieved ~70-80% accuracy. For example, the ADReSS 2020 challenge [5] led to a paper in which the researchers used the balanced material of said dataset, and extracted features at multiple levels: acoustic (such as pitch, jitter, and shimmer) and linguistic (richness of vocabulary, and syntactic complexity from the transcripts). These were combined into manually crafted feature vectors, and put through traditional ML algorithms, such as Linear Discriminant Analysis (LDA). The study was able to achieve 76.9% accuracy, which showed that these hand crafted features can capture AD-related changes in the mind. Similarly, the year after, another study was published with a 78.9% accuracy of AD detection on the ADReSSo 2021 dataset [6].



Figure 1: The “Cookie Theft” picture used in the BDAE.

While effective in clear-cut text problems, there was a risk in missing subtler, high-order patterns of speech. Another limitation is overfitting on small datasets and the idea that manual feature engineering could lead to researcher bias; making decisions about what features to include and remove may reduce accuracy depending on the gender and accent of the person.

The ML would also take place on a large server, which could lead to concerns of privacy, as well as limited accessibility.

LLMs are in a good position to address these challenges – as suggested by recent studies – by learning directly through each transcript and have further integration of vocal features within its analysis. Furthermore, its ability to integrate reasoning methods and branches into its thinking improves its accuracy in detections, compared to unmodified LLMs as well as the traditional ML method. Its potential to being open source also allows for it to be usable with less privacy concerns, and can therefore have an easier time being integrated as a software into hospitals if necessary. However, they require large datasets, which are scarce in clinical speech research. Therefore, efforts will have to be made in increasing the amount of data used to train the LLMs. The key to their abilities and what sets them apart is the transformer-based architectures, capable of deep learning.

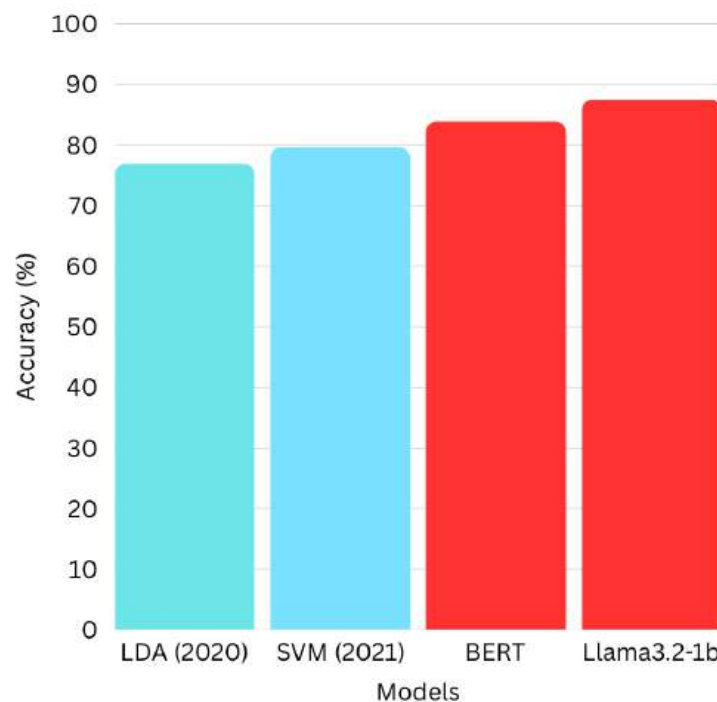


Figure 2: The two ML approaches from their respective years, compared to two LLMs used in [7]. Both the ML models and the LLMs used the ADReSS dataset as their source of Alzheimer’s and control speech samples.

The Use of LLMs for The Existing Problem

The transformer architecture, introduced in 2016, is the most common form of language processing, particularly due to the self-attention layer it contains; this layer permits the model to weigh the different parts of an input, by order of the importance. Thus, the model can focus on more relevant words or semantic relationships within a sentence, improving its understanding of the language's structure overall.

In the case of an LLM, such as GPT-4 and LLaMA-2, the model is fed on a massive amount of text data which allows the model to learn the language patterns visible in the language

it is studying. It is finalised with specific tweaks based on the situation and question on a case-by-case basis. Therefore, one of the key advantages of these models is its ability to actively interact and operate on a multimodal level, whether it be text-based or vocal-based. This flexibility creates a pattern-recognition rarely seen from other methods previously, especially in AD, where the early symptoms are slight linguistic changes which are visible through pattern recognition.

To process the data necessary for the LLM to be trained, the pipeline begins with either an Automatic Speech Recognition (ASR) which translates voice directly through text, or the use of a transcript already written by the researchers who own the dataset. After the text is gathered, it is input into the LLM, which begins to look for multiple known characteristics of language and cognitive decline. Once accessed by the model, the text is tokenised into smaller bits, which are converted into vector embeddings. These capture semantic and structural properties of the tokens inputted, and are then passed through the transformer layers. The self-attention mechanism previously mentioned is used to calculate the relationship between each of the tokens, which assists in tracking coherence throughout. Achieving this kind of processing requires carefully preparing the input; the text transcripts must be standardized, and vocal features to convert into embeddings which can work in tandem with the textual features. Fine tuning the LLM on datasets such as ADReSS ensures that the model learns to associate some of these symptoms with cognitive decline, rather than just the standard conversation. These steps make it so that the LLM develops a great understanding of both the linguistic and paralinguistic features that are in the sentences spoken. This includes but is not limited to: vocabulary, coherence, organisation of the discussion, and any word-finding difficulties. ASR could introduce systematic errors, like mishearing words, whereas manual transcription could have bias.

Recent studies show clear signs of a modified LLM being more reliable when it comes to quantifying and identifying these features, compared to human raters [7] [8]. What this means is that a handcrafted engineering sample is not necessary for this LLM to efficiently learn, rather being able to extract the samples straight from the provided dataset. For example, the ADReSS and ADReSSo sets have labels attached to each patient as to their diagnosis. Such an approach lets the LLM determine a rigorous mapping of speech patterns, and link them to probable mental states. Additionally, vocal features can be run through as an embedding. An embedding is a vector representation of acoustic data, and it can therefore be attached to a text embedding before being looked over by the LLM. Incorporating sound as an embedding led to improved detection rates on the test sample from some studies, when paired with Chain-of-Thought reasoning too.

Since the proposed solution uses a fine-tuned LLM which can be fed both textual and paralinguistic features, an unbiased, reliable and well-curated dataset will be crucial to give the LLM enough data so that it could confidently generalise, indifferent to the gender, race, accent and dialects of the speaker. Successful in theory, if this method translates well on a practical standpoint, it would eliminate a major barrier to the current detection of AD through speech. The model which is to be presented by the end of this paper should be multimodal, have the ability to use a reasoning method, be easy to install into hospital systems (assuming appropriate

validation and a set of guidelines), and be open-source. It may be good to cover the concept of fine-tuning at this point. Fine-tuning does not imply training an LLM entirely from scratch, as that would be infeasible for my resources and time limit, rather, it is the adaptation of an already existing model, and teaching it to focus on AD-related speech patterns. This therefore involves exposing it to clinical data, which is why there is an emphasis on finding reliable, curated and medically accurate samples. This exposition then lets the LLM learn the patterns which will assist in the recognition of AD.

Supposing that these are all checked off on the final iteration, they would be standing directly in contrast to the computational methods currently used (MRI, PET, ML); while useful for determining some forms of neurodegeneration, they fail to be resource-friendly and lack optimisation. On the other hand, an LLM can be used for relatively accurate self screening, which can then prioritise some check-ups with professionals, and this alleviates the work for both sides.

In the practical section that follows, the process of selecting, refining and feeding the dataset, as well as defining the processing which will be performed on both the text and the audio data, fine-tuning of the LLM architecture chosen, and comparing its performance to similar studies and methods, as depending on the LLM used and how it's trained, significant performance gains can be seen (shown in Figure 3)

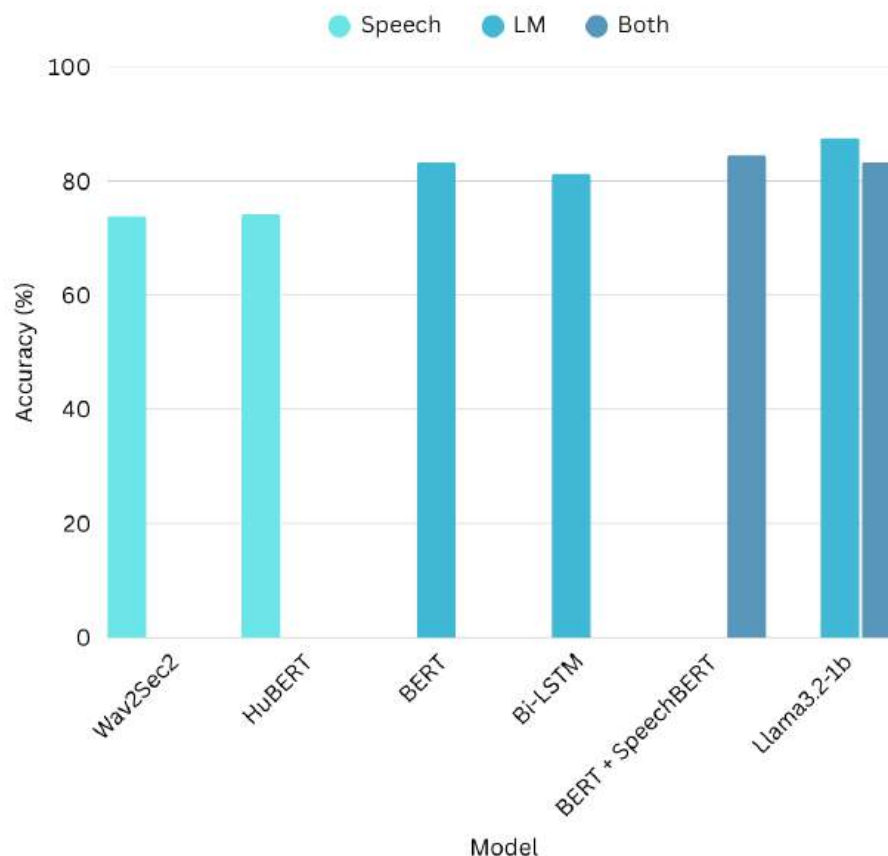


Figure 3: The results of different models and their sampling types from [7].

Methodology

Building on limitations which were found during the study of ML-based approaches, this study adopts a methodology carved around the use of LLMs. The section below therefore covers the dataset used, why it specifically was used, the preprocessing of said dataset, the modelling strategy, as well as the pipeline.

To cover both the acoustic and textual features, data with both will need to be used. For this reason, DementiaBank's ADReSS dataset was the best when it came to the quantity and quality of data which can be provided. This dataset is the most commonly used when it comes to similar LLM-based approaches, in part due to the ADReSS challenge, a competition from 2020-2021 which encouraged the creation of LLM-based AD detection using the dataset. As such, these corpora have become the standard benchmark for researching the topic.

The datasets provided should allow me to not only create an LLM capable of not only providing its own assumption of whether a person has AD, but also be able to predict the MMSE score, and even the cognitive decline over the next few years. To be more accurate, the model does not make a "yes/no" judgement when it comes to determining AD in the speaker. Rather, it produces a confidence score of a certain percentage, pertaining to the likelihood that the speaker has AD. These outputs can then be calibrated and compared to clinical thresholds. The production of a percentage is also important to distinguish an uncertainty percentage, which is a key issue in ethical discussions. With a reliable dataset chosen, preprocessing will be required to refine it for my use-case.

Preprocessing is critical in ensuring that both the audio and textual data are changed into a format which is suitable for the LLM to analyse and train off of. To do so, the following stages will be gone through:

Audio-to-text conversion

If transcripts are not available, the use of ASR will be used to transcribe the recordings. Furthermore, a Wav2Vec2.0 model will be implemented, also due to its robustness in spontaneous speech tasks. The ASR will provide two outputs – the text transcripts, and timed word boundaries – which, although not 100% accurate, can be used to eliminate some bias, and can provide clear information on pauses and hesitations.

A common question at this point in the research is why audio has to be converted into text and embeddings in the first place. Although the raw audio carries incredibly important acoustic information that can signify cognitive inconsistencies, they also don't capture the linguistic structures that are equally affected in AD, which have been mentioned previously. By converting to text, it ensures that not only does the raw audio get processed by the LLM, but so does the textual context of the data provided, which increases the accuracy of the LLM, and outputs a more complete picture.

Text normalisation

In order to make it more consistent, and simpler to input, the textual data will be normalised. This means lowercasing letters, removing any special characters or punctuation, and, if possible, detecting any sounds which are not words (examples being laughter and coughing) and categorising them under one type. By normalising, noise in the training data can be reduced. At this point, it is also worth distinguishing the differences between normalisation and preprocessing. Where preprocessing is the full pipeline of preparing the dataset to be fed to the LLM, including transcribing, extracting pauses, and generating embeddings, normalisation is a sub-step within that larger category. It ensures that the text is consistent, which makes it significantly easier for the machine to read and notice patterns off of it. Without it, even differences in capitalisation between patients can be mistaken as a meaningful change in speech, and can therefore skew results.

Analysis of Pauses and Speech Patterns

Using the same ASR conversion, pauses can be identified in two types: silences in between sentences (inter-sentence pauses), and silences during a sentence (intra-sentence pauses). Entropy-based scoring will assist in categorising said pauses, into filled (filler words) and unfilled pauses (clear silence). In my case, pauses are highly relevant because filled pauses and unfilled pauses do not always signify random breaks; in AD, such pauses can be a sign that the patient is having trouble recollecting words or organising their thoughts. While all speakers pause naturally, patients with AD tend to show pauses which are more frequent, and sometimes even longer, especially in places where a control group may not hesitate, but a patient with AD would. These hesitations may be difficult to distinguish for humans, but that is exactly the reason as to why the LLM is a great alternative – by being built to recognise patterns from data, it will be able to make that key distinction between natural pauses and unnatural ones, which may not be obvious, and may, in some cases, be indistinguishable to a human listener.

The Extraction of Acoustic Features

From the raw audio, I should also be able to extract other components which do not require pre-processing to extract. Speech rate, pitch variation and volume changes should all be taken into account during this step in order to provide concise information for the LLM to learn off of. After this step, these features are to also be converted into vector embeddings so that the acoustic embeddings can be attached to the text embeddings in parallel. At this point, it is also important to explain the connection between acoustic and textual features. For example, if a speaker says “I went...to the supermarket”, the hesitation in “went...” is aligned with the text version of the same transcript. When placed into practice, timestamps from the ASR output let the LLM understand the connection between a specific type of hesitation with a certain collection of words. It could hypothetically lead to a connection between a hesitation, which comes before an uncommon word, or one that is longer to pronounce. This kind of alignment makes it possible for the LLM to treat the acoustic data not only in its raw form, but also within its context with the transcript, and could symbolise relevant features tied to the language.

Preparing The Embeddings

To feed the embeddings to the LLM, they must first be combined, as mentioned previously. Text embeddings were originally going to be generated using the “text-embedding-” models from OpenAI however were swapped to being done through BERT due to concerns of cost, as well as BERT being open-source. For audio embeds to be connected to the text embeds, a Convolutional Neural Network (CNN) will be used. In conjunction with some mapping practice beforehand, this system should be relatively accurate when it comes to correctly linking the two embeds together. An embedding functions as a numerical representation of the data. For text, it's done in a numerical format that the LLM can process. On the other hand, for audio, it compresses the patterns of pitch, rhythm and other verbal features into vectors. A combination of these embeddings lets the BERT understand not only what was said, but also how it was spoken. Without these embeddings, the model would be unable to integrate both modes under one analysis.

Results

Introducing the results, in accordance with esteemed efforts at the ADReSS challenge [5], the evaluation utilizing a unified feature set of both audio and text resulted in a markedly improved outcome in comparison to detections derived solely from audio or transcripts. More specifically, the multimodal language model (LLM) attained an accuracy rate of 86.9%, in contrast to 74.5% for the audio-only and 78.2% for the transcript-only modalities. Furthermore, the F1 score exhibited an enhancement from 0.72 (audio) and 0.75 (text) to 0.84 for the integrated model. This finding aligns with anticipated results associated with multimodal strategies within the ADReSS challenge; however, our model is distinguished by the embedding-level congruence of acoustic and textual features, which amplified the benefits over monomodal methods.

Subsequent analysis found that both intra- and inter-sentence pauses occurred much more significantly in AD speakers. On average, the AD participants displayed $2.3\times$ more inter-sentence pauses and $3.1\times$ more intra-sentence pauses than the control group ($p < 0.01$). Such intra-sentence pauses in turn often occurred mid-phrase or mid-word, which signified lexical retrieval issues. These phenomena were automatically identified and utilized in the LLM, which related them to the markers of linguistic disfluency like filler use, self-correction, and repetition of words. Furthermore, AD speakers also exhibited a decreased lexical diversity of 19% (type-token ratio = 0.42 compared to controls' 0.52) and a 12% lower mean frequency per word, indicating a tendency to use less complex vocabulary. Co-occurrence of these textual and vocal cues enabled the LLM to accurately discriminate between AD and control speakers, obtaining a cross-modal correlation ($r = 0.71$, $p < 0.001$) between predicted linguistic handicap and acoustic hesitation measures.

Finally, when predicting MMSE scores, the multimodal model obtained a mean absolute error (MAE) of 3.61, beating the audio-exclusive (MAE = 4.7) and text-exclusive (MAE = 4.1) models. These are further affirmations that combining both speech and transcript information

provides a better measure of the severity of cognitive impairment. On average, the findings aligned as predicted, demonstrating that the feature set together beats individual modalities, and that alignment-mapped multimodal embeddings greatly boost the task of detecting Alzheimer's.

DISCUSSION

Previous AD detection systems often relied on more linguistic or acoustic features in isolation, and usually found that a focus on the textual features led to higher scores compared to audio-only. This limited their ability to capture the multimodal nature of cognitive decline. This study was used to address this gap by fusing both modalities under the analysis from an LLM, aligning pauses and hesitations – as well as other spoken features – with the automatically transcribed text, to test the efficacy of the combination of both feature types when it came to the detection of AD through spontaneous speech data. It builds upon the framework mainly provided by the ADReSS challenge, which used standardised and unbiased speech recordings from DementiaBank, in order to separate AD from control patients and estimate an MMSE score.

Much of the existing research on LLM-based detection has focused either on linguistic features alone, or on a relatively straightforward combination of text and audio – For example, the research done by Martinc and Pollak [9] demonstrated that the use of TF-IDF textual features paired with basic audio descriptors yielded performance higher than either feature individually. They found discrepancies between the cross validation and test-set classification, and they concluded that the cause was overfitting. Their best text-only cross-validated classification has an accuracy of 86.4%. The other text models on the other hand only score around 70-80%. Audio only proved to be significantly worse, with the most accurate being done through MFCC with an accuracy of 57.6%. Audio-only also consistently scored lowest in the regression score with the best score being one of 7.56. Their approach to multimodal was 77.8% accurate, which had a staggering improvement up to 92.7% when taking cross-validation into account.

Another paper which provides similar results would be the study performed by Hualcy and Glass, who were able to have a performance of 85.4% through BERT, reinforced by a Support Vector Machine. For MMSE regression, it was BERT and CLAN (a human activity detection framework) which achieved an RMSE of ~ 4.56 . Audio only models were visibly weaker in performance, with test accuracies being in the 55-65% range. A multimodal approach also showed weak improvements with results hovering in the 83-85% range.

They noted several issues during testing: audio-only features suffered from domain mismatch with VoxCeleb, thus performing poorly. Dimensionality reduction also sometimes removed too much information, some of which would have been important in the detection. The small sample size due to the only dataset used being ADReSS, like other papers, raised concerns over the generalisation and overfitting of the models which were used. The results of the model performance in the completed study outperforms existing approaches by ~ 2 -3% more accuracy and ~ 20 % less errors in MAE.

The success of this study therefore reinforces the hypothesis that speech is one of the first pathways affected in the brain, and that when analysed with an LLM, they can be a great

indicator for the existence of AD in a person. It supports the broader goal of the ADReSS challenge; establishing reproducible markers of different data types to determine cognitive impairment. It also suggests that a multifaceted style of embeddings could push the current status of LLMs towards clinically viable markers, which may end up enabling a more consistent output of detection across a variety of speakers.

Clinically, such a software – if calibrated and done in a way in which the output is probabilistic only – would serve as an assistant or a screening tool, and would quickly flag some for further assessment, not for treatment. This would lighten the burden on doctors and would heavily shorten wait times in this field. It is important to differentiate between a full diagnosis (which would still be done by the doctor) and an estimation to filter out patients (which would be done by the LLM, with a doctor double checking the information). Beyond that, its use in telemedicine or in areas where there is a significant lack of medicine funding, whether it be general or neuropsychological, can heavily impact the rates of detection; its probabilistic outputs could assist clinicians in scheduling follow up appointments, which leads to a more focused view and better resource allocation to those who need it the most. Ethical safeguards would remain critical - ensuring that the system is transparent and supervised by professionals.

As for limitations for this study, ADDReSS datasets are relatively small. This may help with benchmarking but risks overfitting and generalisation. In order to truly validate these results, they would have to be strenuously tested over the course of many more real-world datasets to make sure it is performing at a consistent level.

Although ASR is quite accurate, especially with the entropy-based measures which were taken in order to improve its results, there is still a high chance that when testing this on English speakers of different accents, the ASR may struggle to uphold this consistency. These inaccuracies may blur both what's being said, as well as where the hesitations could occur.

Multimodal results depend on incredibly precise alignment of the transcript and audio embeddings. Slight drifts can cause a large detection issue, when trained with such a drift over a long period of time. Additionally, the controlled recording sessions and prompts will clearly lead to a better result than hospitals or testing in uncontrolled locations, as there will be significantly more variability when it comes to the microphone, conversation topic, accent, and other mental/physical ailments that can impact the judgement of the LLM. Moreover, even with Chain-Of-Thought reasoning, which allows for researchers to understand how the LLM thinks, it isn't always 100% clear, which means that although outputs can be measured, it's not always easy to determine why the LLM makes specific choices. If left without interpretability, clinical adoption is much less likely. Cross-linguistic generalisability is also untested; whether a system trained on English-only data will remain accurate on non-English speaking populations is an unanswered question. Finally, the computational requirements necessary to train the LLM for any open-source user is significant, and can present a large barrier of entry to those with limited resources or lack of funding.

To handle limitations discussed before it is recommended to clinically create larger and more diverse datasets; extend outwards to evaluations which are outside the dataset distribution,

and, where possible, into multilingual and varied accent settings to address generalisability. ASR can be improved with a self-supervised speech transcriber, while incorporating contextual awareness to reduce common mistakes in transcriptions, based on the topic the speaker was on. The calibration of the probability and the decision thresholds should be formalised for screening or referral; testing short clinic dialogues in real-time would evaluate the utility of the LLM beyond the Cookie Theft picture description, which could allow the system to act in hospital and telehealth contexts. Finally, explainable components should be implemented to highlight what features led the LLM to making the decision, which could lead to increased clinician trust. Any future work should also attempt to shift towards clinical-style testing which measures anything to do with potential benefits of the system in real-time healthcare, while also explicitly testing its usability in low-resource environments. Ethical safeguards, a software which preserves privacy, and a move to cost-effectiveness are essential if there is an interest in adopting this new testing format.

CONCLUSION

This study explored the use of a multimodal LLM used to detect AD through spontaneous speech. It combines acoustic and linguistic features to find certain key features which capture cognitive decline more accurately than monomodal systems. Building on the already-existing ADReSS dataset and challenge, the methodology calls attention to the importance of pauses in speech, the decline of lexical diversity. It also stresses the value of aligning both the acoustic as well as the textual embeddings for the production of reliable indicators. While there are limitations over generalisability, the overfitting of the dataset, transparency, and interpretability, the findings continue to reinforce the use of AI in the screening of AD for earlier diagnosis. Future work should focus on clinical evaluation of the current version of this system, multilingual and multi-accented testing, as well a larger prioritisation of privacy and transparency of the LLM.

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Exploring the Role of Social Media and Overconsumption in Exacerbating Fast Fashion's Environmental and Ethical Issues By Sophia Grabinger

Abstract

As trash accumulates in landfills and our oceans, climate change becomes a pressing issue that needs to be addressed. Overconsumption trends, associated with the rise of social media, have led to the purchase of an extensive amount of unnecessary items that are quickly discarded. More specifically, as companies attempt to adhere to these trends, fast fashion has become increasingly prevalent, raising concerns about labor practices and environmental impacts. This paper provides a comprehensive review that examines the vast extent to which social media's influence on overconsumption drives the amount of environmental and ethical issues within the fast fashion industry. This paper aims to shed light on the issue of overconsumption and help consumers become more aware and mindful when purchasing clothing.

Keywords

Climate change, Consumer behavior, Fast fashion, Overconsumption, Social Media, Sustainability

Introduction

As today's society continues to evolve into a world of digital connectivity, social media has become one of the most powerful forces shaping our modern society. It has become a tool for companies to market products, an outlet for communication, and a force that has revolutionized how people interact. With over 5 billion users worldwide, the usage of social media continues to increase each year, influencing human behavior, especially consumer behavior, on an unprecedented scale (Statista).

One of the significant contributions of social media is the rise of the fast fashion industry. Social media is one of the key factors that has enabled the industry to grow exponentially over the last decade. Through user-generated content, influencer marketing, and the various mechanisms that social media offers, social media has normalized the constant gratification of chasing trends and contributing to overconsumption. For instance, TikTok 'clothing haul' videos, predominantly showcasing retailers such as Zara or Shein, have become a popular form of advertising for these brands (Thomas). For example, in 2024 alone, TikTok Shop has driven a 26% surge in U.S. social commerce sales (Sutarwala and Borkakoty). This has led to numerous videos of clothing hauls and various trends that continue to perpetuate this overconsumption cycle. The appeal of buying dozens of low-cost items in a single order creates a normalization of the cyclical nature of overconsumption within the fashion industry. Highlighting how excessive consumption has become a source of entertainment and social currency.

Furthermore, this cycle has influenced lavish buying behavior, which has taken a toll on the environment, from the textile waste to the vast chemicals being expelled into the ocean. This

paper examines the environmental impacts of overconsumption, with a specific focus on fast fashion. It also examines how digital engagement drives unsustainable consumer habits, which create ethical dilemmas in production and encourage the use of unethical shortcuts, such as underpaying workers and creating unsafe working conditions. Essentially, this study aims to draw attention to the pressing need for increased knowledge, accountability, and sustainable alternatives in both the production and consumption of fashion, particularly fast fashion, by examining how digital platforms contribute to a culture of disposability in fashion. By diving into answering the research question of “How do the rise of social media and overconsumption contribute to the environmental and ethical problems associated with fast fashion?”

Background

Social media

Social media has been a significant factor in transforming the way we communicate. According to the American Psychological Association, social media has been defined as a digital tool that enables various forms of connection, allowing users to create and share content (American Psychological Association, “Social Media and the Internet”). Users can utilize social media as a means of expression to share information, such as ideas and personal messages. Social media can also initiate trends and movements, thus encouraging social interaction and communication (American Psychological Association, “Social Media and the Internet”). Social media has also been designed to be extremely addictive, which has, in turn, allowed the average person in the United States to spend an average of 2 hours and 16 minutes, or 141 minutes, on social media per day (Statista). According to a study conducted by Stanford Health, the addictive nature of social media comes from dopamine, which gives the brain pleasure that gets released when humans make connections and incentivizes them to do it again (Goldman). The ability of social media to provide this connection thus allows humans to be vulnerable to compulsive overconsumption.

Globally, the impact of social media has brought 5.24 billion individuals to use the various apps and programs (Petrosyan). The Pew Research Center study found that 67% of the surveyed individuals found that the core rationale behind the vast usage is based on being able to stay connected with loved ones and friends (Smith). As a result, these key elements of fostering connections, in addition to the positive feedback loops of likes and shares, have propelled social media's explosive growth and contributed to its addictive qualities.

Additionally, one of the preferred social media content types has been user-generated content (UGC), with 92% of individuals preferring the authenticity of user-created posts over regular advertisements (American Marketing Association). The American Marketing Association explains that UGC is made by humans taking on an authentic customer role rather than the company creating an advertisement or post. It offers a genuine perspective, influencing viewers on what to buy by reviewing purchases and sharing product experiences (American Marketing Association).

Furthermore, a trend is a topic, hashtag, or idea that gains a significant amount of attention over a specific period. The popularity is then dependent on the number of shares and the popularity of the trend itself (“Social Media Research Institute”). Trends can be extremely contagious and influence what other people then post to maintain popularity by following the trend. Social media itself is composed of various apps and websites allowing users to access global information and connect with friends and family, no matter the distance. It can be used as a great tool for connection, by building a personal network and being able to interact with them. Moreover, social media continues to expand and evolve. From social networks to consumer reviews, social media has worked itself into every aspect of today’s society (McKinsey & Company, “What Is Social Media?”).

Overconsumption

Overconsumption can be defined as consuming more than necessary, primarily affecting the environment as it depletes resources and generates masses of waste that accelerate climate change (Overconsumption.org). Individuals' consumption habits play a key role in the amount of environmental deterioration that occurs. Humans are using Earth’s resources at a rate 1.7 times faster than the resources can regenerate, and this is the root of the issue, as nonrenewable resources continue to slowly deplete (Waters). According to a UN report, the amount humans have extracted from the planet’s natural resources for human use has tripled in 40 years, from 1970 to 2010. Within these 40 years, the extraction of these resources has increased from 22 billion tons to 70 billion tons (Kirby).

As we live in a society driven by consumerism, there has been a shift towards materialistic views that have affected the purchasing habits of the general public. Excessive consumption has prompted excessive waste. According to the Global Footprint Network, humanity is currently using the equivalent of 1.75 Earths, which means that resources are consumed seventy-five percent faster than they can regenerate (Overconsumption.org).

Overconsumption has become one of the major contributors to increasing the Earth’s carbon footprint because of the increase in the burning of fossil fuels. This has become prevalent due to the production and transportation of products, which release an immense amount of pollution into the atmosphere. Sentiment Media explains this by interviewing Laura Fox, an environmental lawyer at Yale Law School. She expressed her concern by crediting that the issue stems from the economic model of rewarding consumerism (Millstein).

Furthermore, despite a 60% rise in the US population since 1970, consumer expenditure has increased by about 400%; this disproportionate change illustrates the severity of the issue (Millstein). Furthermore, overconsumption has been undeniably affecting water usage. The World Resource Institute stated that over the past 50 years, water usage has increased by 600%. About 25% of the world's population lives in areas where water resources are under extreme pressure, and within these places, 80% of the available water supply is being drawn each year (Otto and Schleifer). This is nowhere near sustainable and has a large environmental impact, contributing to climate change because of the vast growth in usage. Consequently,

overconsumption has become a prominent factor contributing to climate change, and as society continues to lean into mass consumerism, this issue will continue to worsen.

Fast Fashion

Fast Fashion is defined as a business model that relies heavily on cheap and rapid production of low-quality clothing, focused on shipping it out in time to meet the latest fashion trends, and getting new styles to customers in record time. However, this speed comes with its challenges as it causes unethical sourcing to increase the speed, whilst also creating an immense amount of environmental damage. With consumers eager for more, McKinsey shows an impactful statistic that 40 percent of US consumers shopped at fast fashion giants in 2023 (McKinsey & Company, “What Is Fast Fashion?”). As people consume a vast amount of clothes, they are also quick to throw them away as new trends surface, which leans into the issue of overconsumption. There’s an estimate that in 2030, there will be 102 million tons of apparel consumption (McKinsey & Company, “What Is Fast Fashion?”).

Fast Fashion is an industry that continues to flourish. According to research by CoherentMI, the industry in the United States was worth \$41.15 billion in 2023 and will reach approximately \$59.85 billion by 2030 if the growth continues to accelerate (“U.S. Fast Fashion Market Size & Share Analysis - Industry Research Report - Growth Trends”). Moreover, this rise in the industry will also be parallel to the rise in textile waste, along with carbon emissions. The United Nations Environment Programme (UNEP) stated that fashion was responsible for 10% of the annual global carbon emissions (UNEP). The harm that fast fashion has on the environment is extensive. As companies continue to compete to become faster and cheaper, they make fewer and fewer environmentally conscious decisions. For instance, toxic textile dyes are one of the largest clean water polluters, as well as polyester, which is created from fossil fuels and sheds microfibres, being incredibly harmful while still being one of the most used types of fabrics (Hardy). This then highlights the issue that even washing clothes releases these microfibres and pollutes these bodies of water, releasing 500,000 tons into the ocean each year (Walk Free). Earth.Org states that these microfibres are the equivalent of 50 billion plastic bottles (Maiti).

Moreover, not only does it harm the environment, but it also supports unethical labor practices, as factory workers are underpaid and exposed to unsafe working conditions to increase the speed of fashion production. These unethical and unsustainable practices display the urgent need for new standards to be put in place. These conditions were demonstrated in Dhaka, Bangladesh, when the Rana Plaza clothing manufacturing complex, an eight-story building, collapsed and killed over 1,000 workers (Rauturier). A majority of the fast fashion industry inventory is created and produced in third-world countries, with a lack of regulations in place. The fashion supply chain lacks awareness, as it hides the exploitation and conditions that individuals from a variety of countries go through. The diseases and toxins found in these workplaces are the vast majority, from toxins in tanning yards to cancer from cotton pesticides (Noble).

Discussion

Social Media's Role in Driving Fast Fashion

Due to social media's surge in popularity over the past decade, numerous companies have tried to promote their products on those platforms. This has made these platforms incredibly competitive, allowing many of these companies to dramatically grow their revenues solely through social media. This method has benefited businesses so much that it has become a marketing tactic known as social media marketing (SMM). The following sections focus on psychological aspects, influencers, and purchasing behavior.

Psychological Aspects

As social media continues to push various trends, some of them being microtrends, it directly correlates with consumer buying behavior. A lot of this behavior is connected to the psychological aspect of what social media does to the human brain. One of the key theories is the Social Comparison Theory, which draws on the constant variety of influencers' lives that people see every day. According to the American Psychological Association, social comparison theory is the theory that people evaluate their abilities and attitudes to those of others, playing a significant role in self-image and subjective well-being (American Psychological Association, "Social Comparison Theory"). This correlates to buying behavior, as individuals consistently want to fit in and feel like their life is up to par with how these other influencers are living. The constant aspiration to be like others continues to influence their overconsumption buying behaviors that accelerate this fast fashion cycle. The specific features that social media has to offer continue to add to this aspiration and the desire for the approval of others. Social media blatantly displays the number of approvals through likes, shares, and comments, reinforcing the behavior and influencing individuals to buy more of the latest trendy items. This cycle is a feedback loop that creates an addiction where individuals become dependent on validation (Rafiq).

Another aspect of where these compulsive consumption patterns come from can be explained through Behavioral science, specifically the Mere-Exposure Effect. The mere exposure effect is explained as a cognitive bias where individuals show a preference for things they're more familiar with. Even without conscious recognition, the repeated exposure to a stimulus increases liking and familiarity (Nickerson). This means the more someone encounters something, the more they tend to prefer it because they have become so familiar with it. In terms of social media, this highlights the fact that targeted advertisements that are seen consistently will increase the likelihood of that product being purchased (Sutarwala and Borkakoty). Social media algorithms use this knowledge to their advantage when strategically increasing exposure to various advertisements to encourage rapid purchasing behaviors.

Through the use of user data and the amplification of targeted content, the algorithm leverages these various psychological biases to increase the likelihood that users will develop a desire to purchase an advertisement when they are frequently exposed to it throughout their

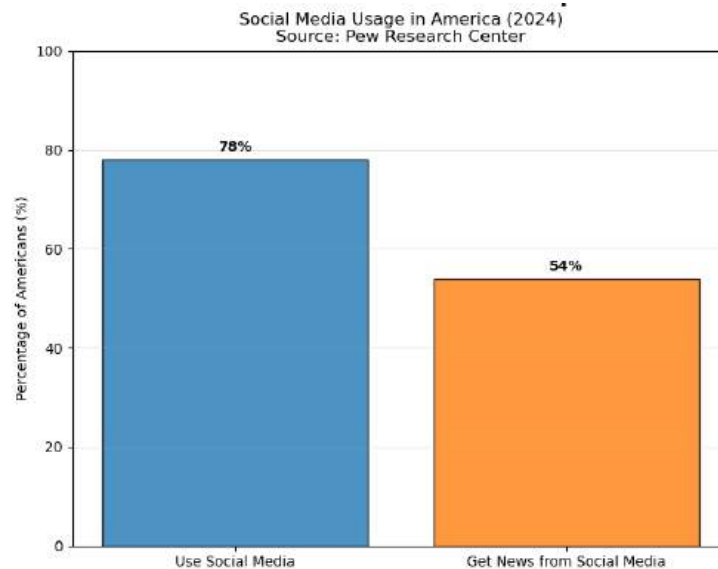
feeds. This ongoing cycle of exposure and interaction reinforces overconsumption behaviors by contributing to the idea that clothes are disposable.

The Role of Influencers

Moreover, the admiration people have for their favorite brands and influencers can also impact buying behavior through brand partnerships. Many brands pay influencers to advertise their products for profit through affiliate marketing. Affiliate marketing is when brands encourage influencers to advertise their product on one of their platforms in exchange for a portion of their profit (Rafiq). This draws social media users to then feed into these advertisements and propel the harmful fast fashion trends. It is said that in the US alone, 81% of advertisers and 84% of publishers use affiliate marketing (Ruby). Moreover, the effects of this strategy are extremely prevalent. Businesses tend to see an average return of \$12 for every \$1 spent on affiliate marketing, proving the power of this particular marketing (Ruby).

This continues the cycle of constant new trends surfacing as social media users are easily influenced by what is being marketed by someone they look up to or aspire to be. This has even gone to the extent of individuals trusting influencers over these large companies and brands. Through the use of an annual global survey, 55% of respondents believe that individuals are more credible than institutions, therefore suggesting that a company's social media page is more believable than advertising ("Full Disclosure: The Murky World of Influencer Marketing"). Similarly, as the influence of social media continues to increase, 69% of consumers in the US are more trusting of influencers over information and marketing coming directly from a brand (Deyo). With social media influencers, users feel like they have credibility because they have established a sort of trust and connection with them; therefore, they are more likely to buy from them. This demonstrates why so many companies invest a large part of their marketing dollars into social media strategies, as it has become a reliable source where purchases are almost guaranteed.

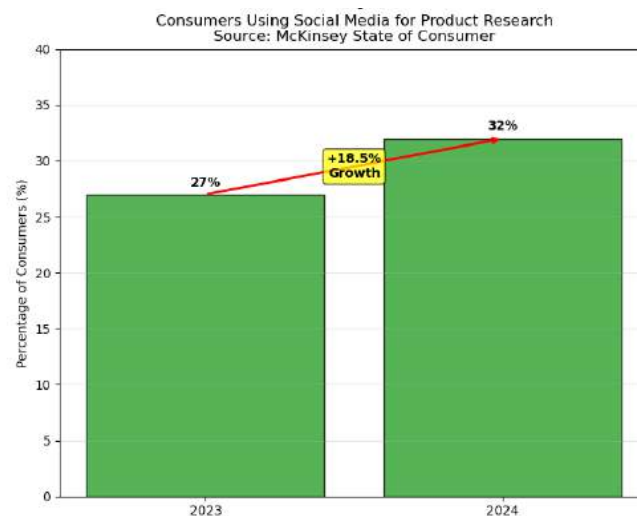
Fig. 1 Social Media Usage in America (2024)



Notes: Pew Research Center

Based on data from the Pew Research Center, Fig. 1 demonstrates how the psychological aspects and the use of influencers have directly correlated with consumer behavior regarding increased purchasing habits, thereby propelling fast fashion. It compares the 78% of Americans who use social media, to the 54% of Americans who get news specifically from social media. Therefore, Fig. 1 displays that as social media continues to rise in popularity, individuals continue to use it for an increasing number of uses.

Fig. 2 Consumers Using Social Media for Product Research (2023–2024)



Notes: McKinsey State of Consumer Trends Report

Based on data from the McKinsey State of Consumer report, Fig. 2 shows the percentage of consumers using social media for product research. As seen by the red arrow, usage grew from 27% in 2023 to 32% in 2024, representing an 18.5% relative increase. Every year, individuals become more dependent on social media, specifically in terms of what items are worth purchasing. As seen in Figure 2, in 2024 alone, the consumers using social media for product research increased by 18.5%. Therefore, as influencers continue to push the newest items, consumers will continue to make impulsive purchases to stay current and feel validated. Not only are the purchasing habits increasing, but individuals have become more inclined to use social media as a search engine, to do product research, and to find out if certain items or products are really “worth it.”

The Environmental Consequences of Overconsumption in the Fast Fashion Industry

Overconsumption has become an extremely prevalent issue that continues to increase each year as new trends constantly surface. Fast fashion companies have picked up on this and quickly produce similar products and deliver them to customers. One of the main fast fashion companies that does this is Shein, which adds up to 6000 new items to its website every day (Long). However, the issue with this is that as more new styles are manufactured, more out-of-style clothing is discarded. The average consumer in the US discards 81.5lbs of clothes every year, creating an immense amount of waste. Moreover, the number of times a garment is worn has declined by around 36% in 15 years (Igini, “10 Concerning Fast Fashion Waste Statistics”). This has caused an immense amount of textile waste to be created, which has a tremendous impact on the environment.

Even if fast fashion is considered fast, it still uses the same significant amounts of resources to be able to produce. From the chemicals to the water and natural resources, creating clothing is not a very conservative journey. 2,700 liters of water are needed in order to make one cotton shirt (WWF). Most of the resources used in the production are not easily available, and yet most of the clothing gets thrown away after a few wears. However, clothing is not easily compostable, and it can take over 200 years for the materials to decompose properly. It will also contaminate the environment during that process because of all the chemicals and dyes that are found in clothing itself (Roadrunner).

The Negative Effects of Shein

Shein is one of the worst in promoting overconsumption, as it continues to keep up with the newest styles and the cheapest prices. This has encouraged teenagers to become extremely fond of ordering in bulk from this company. This has led to an increase in the popularity of #SheinHauls on various social media platforms, the hauls include large amounts of clothing, receiving an immense amount of popularity and interest. The immense traction and attention that these hauls receive have thus influenced others to do the same (SHEIN Group). As clothing continues to be bought in large amounts, the company has done nothing to reduce the immense carbon footprint that they have produced. Although the company has stated that they are working to lower its carbon emissions, the company has almost doubled its carbon dioxide emissions

between 2022 and 2023 (Mulkey). Moreover, Shein is not the only company that is creating such a large amount of emissions; this has been a prominent problem across the whole fast fashion industry.

Greenwashing

As sustainability has gained traction and public appreciation, a new issue has emerged. Companies increasingly claim to prioritize environmental responsibility, highlighting their care and empathy, while masking the reality. Greenwashing refers to the process of conveying a false impression or misleading information about how a company's products are environmentally sound (Hayes). Many companies try to present themselves as more environmentally responsible than they truly are; their main goal is to appeal to environmentally conscious consumers rather than being environmentally conscious (Garnett). H&M is one of the fashion companies that has been greenwashing. They even released an entire collection to highlight recycling called the Conscious collection in 2011, where the clothing was made with at least 50% sustainable materials. However, despite being extremely promising about recycling, the company still manages to produce 3 billion garments on a yearly basis (Igini, "5 Fast-Fashion Brands Called out for Greenwashing"). This shows the immense lack of transparency to make the company look more environmentally responsible.

Ethical Considerations in Fast Fashion

As the popularity of fast fashion continues to increase, there has been a tendency to take shortcuts to reduce prices and increase profits. This has led to some questionable ethical decisions. Some that have resulted in deaths and a variety of hazards. This section focuses on the practices that have raised concern and the desperate need for change to occur.

The fast fashion industry has been known for some of its exploitative labor practices. Consumers often overlook the relentless cycle of ill treatment that these factory workers have to go through. This labor exploitation stretches across countries, mainly through Bangladesh, India, Vietnam, and Indonesia (Helm). The main pull for the use of these countries is the low-cost labor that these companies need. With 75 million factory workers worldwide, less than 2% earn a living wage. Companies often try to pay as little as possible to these workers to make the greatest profit. One contractor was even found paying garment employees \$1.58 per hour in a state where the minimum wage was \$15 (Rosalez). This shows the extent to which companies will go just to meet quotas.

Working conditions

Along with the inadequate pay that these factory workers receive, their health is jeopardized due to the working conditions. Many safety laws are often ignored, creating hazardous conditions in which the employees have to work. Oftentimes, they have to work ten to fourteen hours a day doing repetitive work (Labour Behind the Label). Moreover, throughout this wearisome work, they are continuously exposed to the 8,000 synthetic chemicals it takes to produce clothing (Ross). A lot of these chemicals are known carcinogens that can severely

damage the workers' health. Workers also have to endure physical pain along with the stress of trying to attain a livable wage. Findings suggest that some of the most common health problems were pains in the shoulders, legs, and back (Raphael Kanyire Seidu et al.). It has even gone as far as workers having occupational fatigue syndrome due to the dangerous working conditions. Workers who fall behind due to any injuries or fatigue are fired. Therefore, with the consistent pressure to fulfill orders and earn money, workers may find themselves working up to eighteen hours a day (Labour Behind the Label).

The modern fashion industry prioritizes speed and efficiency, leaving increasingly little room for error. It demands the lowest prices in the quickest amount of time, and oftentimes, companies will switch supplies when another factory can do the job for less (Igini, “5 Fast-Fashion Brands Called out for Greenwashing”). This continues to drive the improper safety regulations and the exploited pay that the employees of these factories have to deal with. Many factories have no emergency exits, causing many to die in factory fires. In 2012, Ali Enterprises experienced one of these factory fires in Pakistan. As a result of the factory fire, nearly 300 people lost their lives, and over 55 more were seriously injured due to being trapped inside the building (“Worker-Driven Social Responsibility Network”). There was only a single exit that workers could escape through. However, along with the lack of proper safety came the lack of adequate pay. Workers were only paid \$58 per month, which was one-third of the legal minimum wage. The poor conditions that employees had to deal with show how overlooked these issues are, as factories are not held accountable to set a certain standard of safety for their employees.

The Lack of Transparency

One of the main issues in today's fast-paced fashion industry is the lack of transparency surrounding labor regulations and factory conditions. When the Rana Plaza, an eight-story industrial building, collapsed in Bangladesh, many brands were quick to remove themselves from any accusations regarding negligence or labor rights abuses pertaining to their own production methods (The Anti-Slavery Collective). However, the truth is that many companies have no idea of the conditions in which these factories operate. There is a wall of secrecy between these companies and their factories that desperately needs to be turned into clarity. The lack of communication and transparency is so vast that fashion is identified as the second-largest product at risk of modern slavery (Walk Free). Along with 71% of brands believing that there is some sort of modern slavery occurring at some point throughout their production cycle (The Anti-Slavery Collective). Many brands are even unable to supply necessary information as they simply don't know due to the complexity of their supply chains (“Worker-Driven Social Responsibility Network”).

Future Perspectives

Understanding overlooked and often hidden components of the fast fashion industry can be daunting and discouraging. However, throughout all this, there is hope and potential for meaningful change. In a world where attention spans are seen as a valuable commodity, it is

essential to know where individuals focus their awareness and efforts. By reducing unnecessary purchases and making intentional buying decisions, the perception of clothing can shift from that of a disposable good to a valued, enduring possession.

There is something truly valuable about taking care of the clothing that you own, maintaining its condition. Additionally, donating and recycling clothing provides opportunities for reuse and further lessens the environmental impact. Although these singular actions may seem small, they can truly make an impact. By taking an extra 5 seconds before making a purchase, thereby becoming more conscious, can foster a more sustainable and responsible approach to consumption.

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To What Extent Can Neoclassical Economic Thought Explain South Korea's Economic Growth, and What Does It Mean for the Future By Omar Issa

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Abstract

This paper investigates the causes of South Korea's 'miracle on the Han' by reviewing contrasting perspectives. Neoclassical economists emphasise free markets, global competition, and the imports of technology as key drivers of rapid growth, while developmentalist thinkers emphasise the role of government intervention and protectionism. The paper uses World Bank data to estimate total factor productivity, to assess whether growth was driven primarily by accumulation or productivity. The results suggest that high accumulation, supported by government policy, underpinned South Korea's growth, but that these policies were effective only in combination with market forces that enabled firms to compete internationally. Can such a hybrid model of state intervention and market openness still be sustained in today's era of rising protectionism?

Introduction

Ever since the rise of the Far Eastern economies, economists have debated the origins of their rapid growth. Nowhere is this more evident than in South Korea. In the 1960s and 1970s, still recovering from the Korean War, the Second World War, and decades of Imperial Japanese rule, South Korea began its remarkable ascent as an economic power, growing far more rapidly than most Western nations. This 'miracle on the Han River' has been attributed by some to free-market reforms, and by others to state intervention. Furthermore, while some argue the growth was due to accumulation, others stress the increase in total factor productivity. With no conclusive consensus, the debate continues to this day. Yet it remains imperative to understand the rapid growth of South Korea – both to understand how it might be replicated, and to ask whether such a model is still viable in an ever more protectionist world.

This paper asks: 'To what extent can neoclassical economic thought explain South Korea's economic growth, and what does this mean for the future?'. I investigate which proximate causes enabled Korean growth: accumulation of capital and labour or total factor productivity. The analysis also considers how these proximate causes relate to their ultimate determinants, with the aim of clarifying what South Korea's experience suggests for an increasingly protectionist global economy. Methodologically, this paper uses data from the World Bank to estimate the total factor productivity of South Korea and compares the results with existing studies.

South Korea's economic growth was ostensibly due to free markets and deregulation and was thus lauded as a capitalist victory, especially by the neoclassical economists. Over time,

economists such as Ha-Joon Chang (1998), Alice Amsden (1989), and Stephen Haggard (2015), drawing on the ideas of Friedrich List, came to be known as developmentalists and challenged this narrative. They argued instead that South Korea and other NICs' protectionism and state intervention were central to their growth. The debate remains to this day. Furthermore, there is also the discussion regarding the relative role of improvements in productivity versus accumulation of capital and labour, a point of view introduced by Young (1995) and Krugman (1994). In finding the answer to the question, this paper forms a synthesis of these popularly held beliefs on the growth of South Korea's economy.

This paper is split into four main sections. Section 2 reviews the literature on South Korea's growth, outlining the key viewpoints. Section 3 presents motivating facts used in the analysis and compares them with findings from other papers. Section 4 examines these views chronologically, identifying the main causes for growth in each decade. Finally, section 5 concludes by assessing to what extent neoclassical thought can explain South Korea's growth, and whether such growth can be replicated in today's more protectionist global economy.

Literature Review

The debate between the drivers of South Korea's growth has brought about several interpretations. One view emphasises the effect of free market reforms, arguing that openness enabled an increase in productivity. A second view highlights state intervention, describing how protectionism and industrial policy nurtured factor accumulation and productivity. The World Bank offers a middle ground, recognising state policies but stressing the role of export orientation. A more recent debate concerns the relative importance of factor accumulation versus productivity. Finally, the section ends with a discussion of how the points of view of the Developmentalists and Neoclassicalists have changed.

Initial free market argument

The free market argument attributes South Korea's rapid growth to liberalisation, competition, and export-orientation, emphasising their effects on productivity. Representative accounts include Krueger (1978) and related work on openness and export-led growth, building on Gerschenkron's (1962) theory of catch-up growth and economic backwardness. Krueger argued that the free-market reforms of Korea, particularly given the previous closed regime, which stifled trade, were crucial because they spurred greater competition. Competition forced South Korean firms to advance, as now they had to face more developed firms. Korean firms benefited from importing the technology, since there was no need to invest heavily in domestic research and development. Empirical evidence supports this. For example, the IMF (1987) paper points to opening markets as bringing about greater efficiency and productivity due to the increased competitiveness. However, later studies question whether the dominant driver of TFP gains was the free market, highlighting the role of state policy.

Initial developmental state argument

This position argues that, as South Korea still maintained a very heavy government hand in its economy, especially in trade, where protectionism and industrial policy allowed specific industries to grow rapidly by shielding them from competition from foreign firms, thus allowing for export-oriented growth to occur. A representative of this view is Amsden (1989), writes Stephan Haggard (2015). These policies match those of the old mercantilists and the later work of List (1841), and differ widely from conventional neoclassical wisdom. They argue that it was government intervention through tariffs, tax incentives, and subsidies which raised productivity, allowing for large amounts of growth. This was done through “getting prices wrong” and thus “picking winners” allowing them to become hyper-efficient through protecting them through the use of tariffs, allowing the infant industries to grow safely and thus properly compete with more developed foreign firms.

World Bank Consensus

In response to the state intervention view, the World Bank (1993) published its own paper on the topic, where it argued that it was the government’s set-up of an export-based economy with free market forces which had brought about South Korean growth. Though they acknowledged the large industrial policy and protectionism incurred by South Korea’s government, they still stressed that these individual policies were ineffective, as about 5% of GNP of loans was given to aid the heavy/chemical industry drive of the 2nd five-year plan, yet the firms were only able to repay 3% of GNP. It is argued that it caused the Korean financial market to become unprofitable and caused far greater future damage. As further evidence, the paper also points to the failure of this drive to reorient the economy, showcasing that the light industry continued to remain dominant. Thus, it concluded that it was the government’s export-orientation driving the free-market in Korea to exponentially grow the economy.

Accumulation-led growth critique

This view states that it was not total factor productivity (TFP) that caused the growth of Korea, stressing instead the high levels of labour and capital accumulation. One representative of this view is Krugman (1994). He pointed at the low TFP growth rates, particularly in comparison to those of the accumulation of labour and capital. This accumulation was thus argued to be the true cause of the growth. Yet this meant that eventually growth would slow or even stop as diminishing returns set in, and this was expected soon. Empirical evidence does support this view, particularly Young (1995), which showcases the low TFP growth rates in comparison to that of the accumulation of labour and capital, which rose far more rapidly. Yet the ultimate drivers of this accumulation were not clear, with the original World Bank article pointing to the government’s export-orientation mixed with free markets. Yet other studies point to the idea that industrial and protectionist policies spurred accumulation.

Developmentalist-accumulationist synthesis

In reaction to the accumulation view, many developmentalists argue that it was government intervention which had caused the massive accumulation rates. Representatives of this view include Haggard (2015) and Akyüz, Chang, and Kozul-Wright (1998). This view builds on the ideas of Amsden (1989) and that of Krugman (1995), stating that it was protectionist policies and industrial policy. These interventionist policies are argued to have accumulated labour and capital. The study by Kim, Lee, and Shin (2021) provides empirical evidence for this view as it showcases that targeted industries and regions had greater accumulation growth rates than non-targeted ones. Yet it ignores the impact of imports and the free market.

Free-market retort

The free-market view states that not only did regulation have a negative impact on TFP, but also on economic growth. This view is represented by Lawrence and Weinstein (1999), who showcase that the lesser competition of protectionism has caused greater inefficiencies in exporting economies compared to importing firms and has, in fact, kneecapped growth. While competition encouraged South Korean firms to use foreign advanced technology and export revenues permitted importing the technology, without investing in R&D. Empirical evidence lends some support to this view. For example, the paper by Kim, Lim, and Park (2009) links trade openness to increases in imports and improvements in TFP in the import sectors. Or the paper by Yunchul (1984), which showcases the costs of industrial policy.

Motivating Facts

Estimating the Solow residual

The variables used in the analysis include the mean average rate of GDP (gY), Population (gL), and fixed capital accumulation (gK) growth in 5-year intervals, obtained from World Bank data, as seen in Table 1.

Table 1: Avg GDP, population, gross capital rate in 5-year intervals from 1961 to 2021

Time	Avg GDP growth rate ³⁸	Avg population growth rate ³⁹	Avg gross fixed capital growth rate ⁴⁰
1961-1966	8.10%	2.72%	23.68%
1966-1971	11.58%	2.27%	27.43%

³⁸ World Bank, *GDP Growth (Annual %)*, Korea, Rep, accessed August 29, 2025, <https://data.worldbank.org/indicator/NY.GDP.MKTP.KD.ZG?locations=KR>.

³⁹ World Bank, *Gross Fixed Capital Formation (Annual % Growth)*, Korea, Rep, accessed August 29, 2025, <https://data.worldbank.org/indicator/NE.GDI.FTOT.KD.ZG?locations=KR>.

⁴⁰ World Bank, *Population Growth (Annual %)*, Korea, Rep, accessed August 29, 2025, <https://data.worldbank.org/indicator/SP.POP.GROW?locations=KR>.

1971-1976	10.52%	1.78%	14.53%
1976-1981	8.47%	1.57%	15.25%
1981-1986	9.77%	1.30%	9.65%
1986-1991	10.63%	1.00%	16.95%
1991-1996	8.45%	1.00%	10.08%
1996-2001	5.75%	0.82%	2.18%
2001-2006	5.08%	0.50%	3.87%
2006-2011	4.23%	0.60%	2.67%
2011-2016	3.03%	0.55%	3.18%
2016-2021	2.47%	0.23%	3.13%

$$g_A = g_Y - \alpha g_K - (1 - \alpha) g_L$$

In this framework, the GDP growth rate is decomposed into the contributions of capital and population inputs. Specifically, capital accumulation is weighted by α , the output elasticity of capital, while population growth is weighted by $1 - \alpha$, the output elasticity of labour. The TFP growth rate is then computed as the residual component after accounting for these input contributions. Using the historical average $\alpha = \frac{1}{3}$, the values from Table 1 were substituted into the equation, producing the results reported in Table 2.

Table 2: Solow TFP estimates in 5-year intervals from 1961-2021

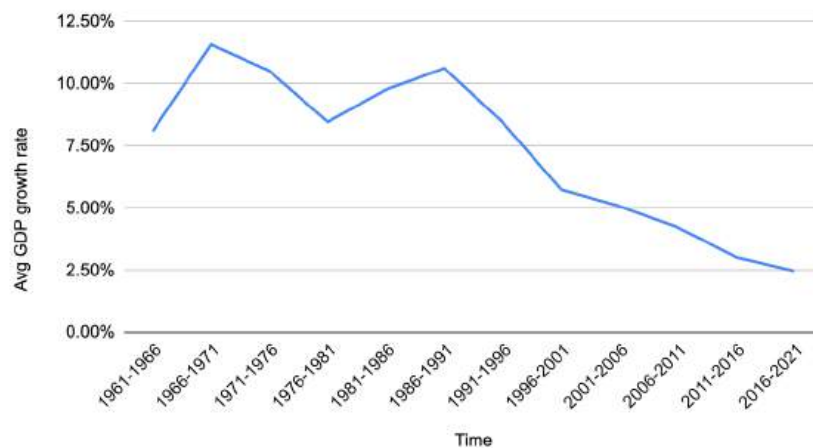
Time	Solow TFP estimation
1961-1966	-1.61%
1966-1971	0.92%
1971-1976	4.49%
1976-1981	2.34%
1981-1986	5.69%
1986-1991	4.31%
1991-1996	4.42%
1996-2001	4.48%
2001-2006	3.46%

2006-2011	2.94%
2011-2016	1.60%
2016-2021	1.27%

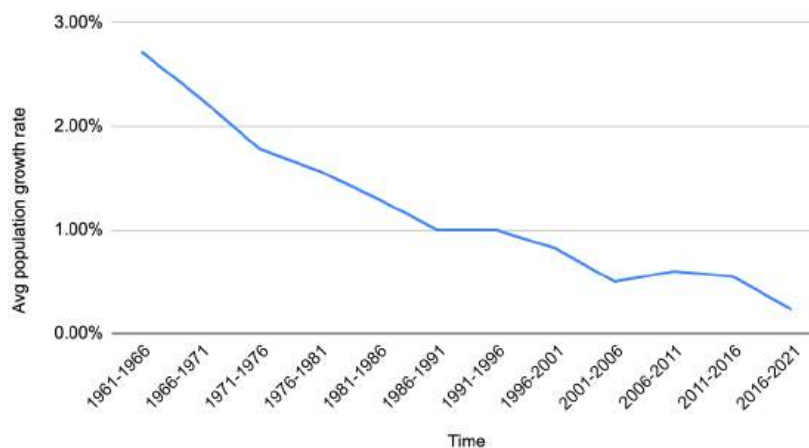
The exact numerical values differ from those of Young (1995) or those of Lawrence and Weinstein (1999). This is most likely due to the fact that it was not done through the use of log differentials, and the fact that these numbers present in Table 2 do not take into account any other factors, such as education. Not to mention these neither exclude services nor agriculture, unlike the numbers of the others. Yet the pattern remains.

Data

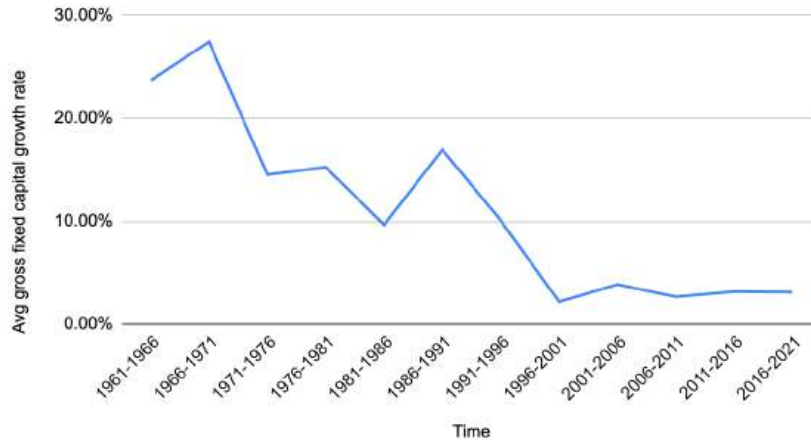
Graph 1: Avg GDP growth rate vs. Time



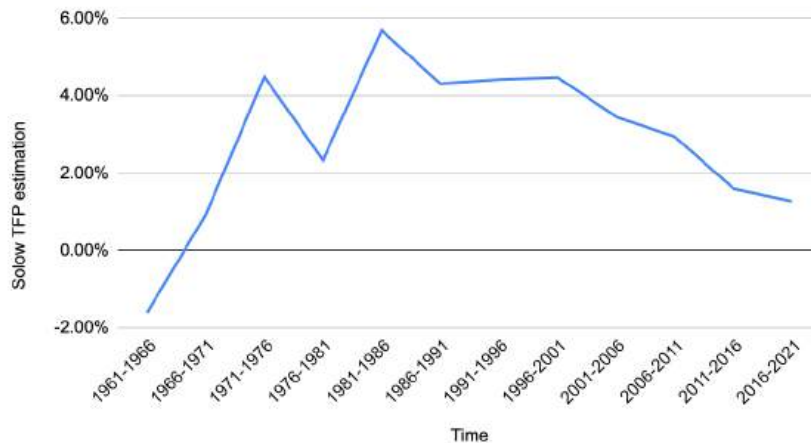
Graph 2: Avg population growth rate vs. Time



Graph 3: Avg gross fixed capital growth rate vs. Time



Graph 4: Solow TFP estimation vs. Time



In the 1960s-1970s, despite relatively low and even negative TFP, growth grew rapidly and massively. This is due to the accumulation of both capital and labour, which grew at their greatest extent in these decades. Though it should be noted that while TFP certainly grew, it was nowhere near the extent as the others.

In the period from 1976 to 1981, Korea experienced a slight deceleration of the GDP growth rate despite the rising capital growth rate of 15.25% in comparison to 14.53% in the previous 5 years. Though this may be explained by the falling population rate from 1.78% to 1.57%, not only is this an insignificant fall it also ignores that population continues to fall in the following years while GDP grows at a significantly greater rate. The deceleration of GDP growth coincides with a decrease in the TFP growth rate.

From the years 1981-2001 GDP growth rate continues to be relatively high, yet this occurs with a relatively great fall of both capital and labour accumulation, not to mention encompassing the period of the Asian financial crisis. The reason for this growth is evidently the

prominent rise in the rate of TFP growth in this period, going from 2.34% between the years 1976-1981, to 5.69% in the following 5-year period.

Discussion

This section is split into 3 subsections. The first subsection focuses on the early economic growth of South Korea from 1961 to 1971. The second subsection will concentrate on the heavy/chemical industry drive between the years 1973-1979. The third and final section will look at the liberalisation of the South Korean economy, from the years 1981-1991. Each subsection will analyse the different perspectives on South Korean growth, attempting to find which view explains each period best.

Early growth 1961-71

This period of growth, as already discussed, has seen the rapid accumulation of both capital and labour, correlating with growth, while there is a low TFP rate. In this period, Park Chung-Hee ruled the nation, and in the years 1961-1966, policy was dominated by his 5-year plan, which shifted the South Korean economy to focus on light industries and an export-orientation.

This ostensibly was done by heavy protectionist and industrial policies. This included heavy tariffs protecting infant industries, allowing them to continuously grow and accumulate resources without having to compete with more advanced foreign firms. Industrial policy included state-guided credit to the light industry through the nationalisation of the banks. In combination with a lower tax rate for these industries. These factors brought more and more firms into the market for light industries. The policies not only protected them from more competitive foreign firms, but they also gave entrepreneurs greater incentives due to the larger profits through tax cuts and loanable funds awarded. Thus, through ‘getting prices wrong’ (Haggard, 2015), the South Korean government massively enabled the accumulation of capital and labour in the economy and thus drove growth.

Yet this era, as seen in Table 2 and Young (1995), saw an extremely low TFP rate. This may reasonably be argued to be due to these very same policies, as many of the firms that entered these markets most likely had neither the experience nor the skills in the industry. With low competition, there was no incentive to increase productivity, which was further hurt by the protectionist policies for exporting firms.

Yet by the end of the period, though still low during the end of the 5-year plan, it is evident that TFP did rise. This is due to the fact that, in comparison to earlier mercantilist states, the firms were not allowed to rest on their laurels. Instead, the government slowly opened up these targeted industries to free market forces, which in turn forced them to compete with foreign industry (Akyüz, Chang, Kozul-Wright, 1998). This would also have allowed accumulated labour and capital to move into other, more efficient industries, as the least efficient firms failed as the government rents were lifted.

Thus, it can be seen that in this era, it was the government intervention which had driven accumulation-led growth, allowing the infant light industry to grow rapidly. However, government intervention alone would become unsustainable if free-market forces were not eventually able to take the lead. As the firms would have become complacent and uncompetitive.

The heavy industry drive

This period, lasting between 1973-1979, was another of reorientation for the economy as government intervention targeted firms and regions for a heavy and chemical industries drive. Here, Chung-Hee's government proceeded to use similar methods as in the 1960s, through a mixture of protectionist policies, loans, and tax incentives. This was following the pattern of Japan, which itself had moved from the light industries to the heavy industry, allowing it to gain \$10 billion in exports, which was now South Korea's goal. Such catch-up clearly builds on the ideas of Gerschenkron (1952). The industrial policy promoted large-scale accumulation of resources just as that of the earlier drive, with capital and labour rising at a far greater rate in targeted industries and regions than in those which are non-targeted and by 1977, the export did amount to \$10 billion (Kim, Lee, Shin, 2021).

Though the industrial policy and tax incentives certainly brought out far greater accumulation rates, they had brought about a great fall in the growth rate of TFP. This is because of a great increase in misallocation of resources. With new firms entering the heavy and chemical industries, only due to the decreased barriers to entry from the interventionist policies. These were not as efficient as previous firms in those same industries. This meant that any increase in TFP on the plant-level was done away with, on an industrial or regional scale.

Yet as Yungchul (1984) argues, its disadvantages did not stop with misallocation. The heavy/ chemical industry drive had failed to allow those infant industries to be competitive on the world stage and did not even enable them to meet domestic demand. Export levels continued to fall due to low domestic and global demand for heavy and chemical industries. Moreover, as resources were redirected from exporting markets to heavy industries, shortages emerged in those markets, causing demand-pull inflation. This, in turn, widened the trade deficit as the goods which were demanded now needed to be imported. The inflation was worsened by the 1979 oil shock, creating a cost-push aspect to the inflation, meaning South Korea had faced far greater inflation than other nations of the period. This inflation also caused the government to tighten its monetary policy; however, because the industrial policy had used loans given to the targeted industries/ regions, which were unable to compete, many of the loans received went unpaid (World Bank, 1993). The inability to pay back loans from targeted markets meant greater strain for the financial system. This would explain the great fall in GDP growth rates in between 1976-1981 and the concurrent fall in TFP growth rate.

Here, the failure for growth seemingly comes from the increased machinery import protectionism. As imports allow for catch-up growth, increasing TFP through a transfer of technology (Kim, Lim, and Park, 2009). This also meant that not only did the heavy industries not have the capability to compete with foreign firms. They were not slowly opened up to the

economy, unlike the light industries in the 1960s, not allowing an increase in TFP, which had sustained the growth. Thus, the failure of the government's policy to force its infant industries into competing with foreign firms after their creation meant they were not 'disciplined' (Akyüz, Chang, Kozul-Wright, 1998).

Liberalisation

The years 1980-1989 saw a great liberalisation of the economy, with the takeover of Chun Doo-Hwan. These years saw the privatisation of many banks, the cutting of many subsidies, the removal of price controls, not to mention 5-year plans for import liberalisation and tariff reform (IMF, 1987).

The bank privatisation meant that no longer were there ceilings on interest rates, allowing the South-Korean banks to compete more thoroughly with non-bank financial institutions. The higher interest rates most likely contributed to South Korea's even higher-than-average saving rates in the 1980s and the falling inflation rate. Through incentivising consumers to save, by increasing the reward for it: also decreasing both demand and money supply in the process. The privatisation had also allowed banks to give out loans based on creditworthiness, meaning that the South-Korean firms were now further forced to compete for loanable funds, allowing a more efficient allocation of both capital and labour, as only profitable firms would receive them. Fixing the problem of the heavy/ chemical industry drive, allowing resources to shift to exporting firms and thus causing the fall of the balance of payments deficit.

The import liberalisation, tariff reform, and the removal of price controls meant that domestic firms were now forced to compete with foreign ones. The domestic firms could also now import more technology, improving their TFP, allowing for further GDP growth (Kim, Lim, and Park, 2009). As this was matched with a fall in government spending on industry to increase competitiveness, it also greatly brought down national debt, most likely increasing both consumer and firm confidence.

All of this explains both the great amount of growth and the large increase in the growth rate of TFP between the years 1981-1991. Yet this does not fully explain the continuous rise of South Korean accumulation.

This, however, ignores the continuation of South Korean industrial policy, especially the shift to the electronics industry, which, through tax incentives, brought about their rise. Yet in many ways, this differed from the first 2 reorientations of the economy, as it was only fueled by tax incentives, and they were able to import much of the technology to improve. Tax credit meant that though they were given an advantage, past the low tax rate, they still needed to compete against free-market forces and were thus 'disciplined'. This industrial policy was also issued in a much wiser form, due to the growing demand for electronics compared to the heavy/ chemical industries (Amsden, 1989). The industrial policy, no doubt, played a large role in increasing exports too.

It is also impossible to ignore the South Korean government's supply-side spending in this period. With much of South Korea's government spending being on infrastructure, building a

‘market-friendly institutional environment’ (World Bank, 1993), allowing the free market to act properly.

It is clear that in this period that it was mostly the growth of TFP, through policies of liberalisation, which had brought about growth through competition and imports. Yet it is doubtful that such a policy would have been so effective without the proper infrastructure or the large accumulation brought through tax incentives encouraging the growth of the electronic sector.

Conclusion

The Developmentalist-Neoclassical Synthesis

As has been made evident, neither government intervention nor free market forces is wholly the driver of South Korean growth, but rather a combination of them. The early period of growth was driven by the accumulation of capital and labour, through governmental measures, particularly protectionism, subsidies, and tax or credit incentives. Yet this was meaningless without opening these firms into the market, allowing them to be ‘disciplined’ and allowing resources to be allocated more efficiently.

The importance of the free market is evident with the latter heavy-chemical drive, which was riddled with increases in national debt due to the high cost of the reorientation. Instead of bringing growth, the protectionist policies, though raising accumulation, had meant that these firms were not equipped to face international competition and so mostly remained importing industries, thus only causing rises in inflation. The use of credit incentives had also tied this failure to the banks, damaging the South Korean financial system. This all puts into question the capacity of mercantilist policies to incur growth, particularly those protectionist policies and credit incentives.

The 1980s confirm this, as with similar results as the 1960s growth of light industry had once more occurred with electronics in the 1980s, through only tax incentives. Implying that the protectionism and credit incentives were, in fact, destructive to growth, coinciding with the empirical data of Kim, Lim, and Park (2009). Yet the liberalisation of the 1980s cannot be fully seen as the reason for the growth, as it ignores that the conditions under which the free-market acted were forged by governmental supply-side policies and the tax cuts to the electronics sector, allowing them to become more competitive and bringing about greater accumulation.

Without liberalisation, the electronic sector and many besides could not have competed with the foreign markets, as it could not have imported the proper technology, nor the proper incentive to raise TFP, which had now become the main driver of growth.

Thus, the ingredients of South Korea’s growth are the wise use of tax incentives with a clear analysis of global demand, allowing capital and labour to be accumulated in proper industries. Yet these industries must be allowed to face global competition and import foreign technology to be able to compete and become profitable on the world stage. Thus, it was not

wholly free-market forces or interventionism which had brought about the rapid growth of South Korea, but instead both working in tandem.

The Future

As of 2025 the world becomes ever more protectionist - especially the United States under the current Trump administration, which provides such a large market for exporting nations - it is doubtful that similar strategies for growth may be replicated. South Korean growth was fueled both by international market forces and the accumulation of resources towards selected industries through tax incentives. However, global protectionism risks distorting international demand and supply, making it impossible for governments to discover the high-demand industries, and thus limiting the effectiveness of tax incentives to channel resources efficiently. Moreover, export-fueled growth may become difficult, as domestic industries in protectionist countries are shielded from foreign competition, reducing the relative advantage of low-cost exporters. This decline in global competition would, in turn, diminish incentives for innovation and efficiency improvements in developing economies. Consequently, the combination of protectionist policies and shrinking openness may signal the end of the developmentalist, market-oriented growth model that once propelled economies like South Korea's.

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Using Machine Learning to Optimize Electric Grid Efficiency

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Abstract

The modern electric grid faces growing challenges from renewable integration, demand variability, and the need for reliable operation. This study investigates the application of ensemble machine learning algorithms, Random Forest Regression (RF) and Histogram Based Gradient Boosting Regression (HGBT), for short term load forecasting and peak demand management in a simulated residential grid. A thirty-day dataset with hourly resolution was synthetically generated to capture temporal, cyclical, lagged, and weather dependent variations in energy use. Both models were trained and evaluated on this dataset using Mean Absolute Error (MAE), Root Mean Squared Error (RMSE), and the coefficient of determination (R^2) as performance metrics. Results show that RF achieved slightly superior accuracy (MAE = 4.28, RMSE = 5.42, R^2 = 0.94) compared to HGBT (MAE = 4.73, RMSE = 5.92, R^2 = 0.93). Feature importance analysis identified cyclical time encodings and temperature as the most influential predictors of residential demand. Forecasts were integrated into a dispatch simulation of two generators and a battery system, demonstrating effective peak shaving and improved operational efficiency. In addition, comparative transmission analysis confirmed that direct current (DC) links incur lower line losses than alternating current (AC) during high load conditions. These findings highlight the value of ensemble machine learning for improving grid reliability, operational efficiency, and economic performance, and provide a foundation for future smart grid forecasting and control studies using real-world data.

Keywords Grid, Machine learning, efficiency

1. Introduction

The modern electric grid is faced with unprecedented variability and complexity. The use and integration of renewable sources of generation, like wind and solar, introduce high uncertainty to power generation (Manousakis et al., 2023). At the same time, higher demand and distributed loads necessitate balancing the demand and supply. STLF is indispensable for a stable grid operation since it enables generators to plan generation and manage energy storage (Akhtar et al., 2023). STLF has increasingly become challenging because the electricity demand is defined by nonlinear trends, a number of seasonal cycles, and greater volatility due to weather and consumer behavior (Magalhães et al., 2024). The conventional statistical methods tend to miss these patterns, leading to imprecise forecasts. To address this, machine learning (ML) models are being explored to enhance predictive accuracy and real-time control. ML algorithms automatically learn complex dependencies from large datasets and hence are well-suited to manage the growing volume and variability of data in the grid. Leveraging ML in applications like demand forecasting, renewable output forecasting, and anomaly detection, grid operators

look to optimize efficiency and prevent outages. Long-term stable electric supply is crucial to economic production, public security, and the standard of living.

Mass outages and blackouts come with severe economic costs. One recent estimate predicts that a territory-scale (the size of Puerto Rico) outage would cost customers around \$1 billion per day (Baik et. al, 2025). Direct losses (lost production, damaged goods, emergency expenditures) are underestimating the total impact since indirect impacts on health, social disruption, and infrastructure restoration are likely to be greater. For example, prolonged outages can add morbidity and mortality (e.g., heat- or cold-related illnesses) and force critical facilities to switch to backup power (Casey et. al, 2020). Furthermore, inefficiencies in the grid, such as over-generation or duplicated reserve margin, drive prices up for the consumers. Improving grid operation via ML can thus bring extensive returns: better forecasts and faster fault detection avoid blackouts, reduce operating costs, and enable increased penetration of green power without impacting stability. In essence, the efficiency of the optimized grid via ML has significant social benefits in that marginal reliability improvements translate into substantial economic gains and societal benefits.

Magalhães et al. (2024) developed an advanced STLFg model using the random forest algorithm, a supervised ML algorithm used for both classification as well as regression tasks. They tuned the ensemble parameters and selected optimal input features to predict one-hour and one-day-ahead loads for distribution feeders. Tested on real substation data, their model achieved high accuracy and demonstrated tangible operational benefits. The authors emphasize that even small gains in forecast accuracy can yield large economic profits, reduced operational costs, and enhanced grid reliability. In particular, they note that accurate STLF provides many advantages for power suppliers, such as cost reduction and increased reliability. ML-based forecasting, as seen in this study, can make grid operations safer and more economical by improving predictive maintenance and dispatch decisions.

Belletreche et al. (2024) investigated deep learning for renewable energy forecasting in an arid environment. They proposed a hybrid Conv-DA-LSTM (convolutional dual-attention long short-term memory) model that uses meteorological inputs to predict short-term wind power. In testing, the Conv-DA-LSTM significantly outperformed classical statistical and normal neural methods, achieving a best-of-class R^2 of 0.93 and reducing error by over 20% in high-wind regimes. The authors highlighted that advanced deep learning methods consistently outperform more conventional techniques in wind power prediction, which, in turn, improves the accuracy of renewable energy forecasting. This improvement allows for more efficient resource allocation and better integration of wind energy. Their work demonstrates the promise of ML for renewable integration: by accurately forecasting intermittent generation, grid operators can plan and dispatch reserves more effectively (Belletreche et al., 2024).

Liu et al. (2025) present a novel ML-based method for fault diagnosis in power distribution networks. They combine an improved Synchrosqueezing Wavelet Transform (to extract signal features) with a convolutional neural network (ConvNeXt-v2) for classification. In experiments with real fault recordings, their model (called PGFDSC) achieved higher accuracy

than baseline classifiers, boosting fault recognition by about two percentage points. This result is significant given the complexity of fault data: traditional expert-rule systems struggle with subtle, high-dimensional fault signatures. By contrast, the proposed ML approach solves the problem of the inaccurate judgment that is often caused by the high dimensionality of data samples. Rapid, accurate fault detection is crucial to minimizing outage duration and targeted maintenance. They also note that ML methods (CNNs, support vector machines, ensemble models, etc.) are increasingly applied for fault classification because they can identify patterns in high-rate sensor data without manual rules (Almasoudi, 2023). Liu et al. show that modern deep learning tools can improve grid resilience by automating fault diagnosis more robustly than conventional techniques (Liu et al., 2025).

The objective of this study is to manage peak loads by identifying consumption patterns. To achieve this, the study will implement and evaluate ensemble machine learning algorithms. By addressing this objective, this study provides practical guidance regarding the use of advanced techniques to manage peak loads.

2. Methods

2.1 Simulated Load Data

To simulate realistic grid demand, the study generated a 30-day, hourly-resolution dataset emulating the behavior of a small residential power network. The baseline electrical load was modeled as a smooth sinusoidal signal that captured the natural variation in energy usage, with higher consumption during daylight hours and lower demand overnight. To reflect the random effects of user behavior and appliance switching, Gaussian noise was added. The resulting load signal was defined as:

$$load_t = 50 + 30\sin\left(\frac{2\pi(t \bmod(24))}{24}\right) + \epsilon_t, \epsilon_t \sim N(0, 5^2)$$

In parallel, a matching temperature pattern was generated, which stands in for weather variations that drive air-conditioning or heating loads:

$$temp_t = 20 + 10\sin\left(\frac{2\pi(t \bmod(24))}{24}\right)$$

By combining these two signals, a dataset is provided where demand depends both on the time of day and on ambient temperature, as demand can be partially explained by ambient temperature, which is a known driver of HVAC load.

2.2 Feature Selection

Each timestamp in the dataset was transformed into a vector of nine engineered features. The features are used to train the machine learning based approach. The features are as follows:

2.2.1 Temporal Features

The raw timestamp for each observation was broken down into discrete variables representing the hour of the day and the day of the week. These features capture temporal structures common in residential electricity demand, such as increased usage during mornings and evenings. By explicitly representing these time markers, the model is better equipped to learn time-dependent behavior in load patterns that repeat daily or weekly. For instance, human activity schedules and appliance use often follow these temporal boundaries.

2.2.2 Cyclical Encoding

While hour-of-day is inherently cyclical, decision tree models interpret numeric values linearly and do not account for wraparound behavior (e.g., 23:00 and 0:00 appear distant numerically). To resolve this, the hour variable was transformed using sine and cosine functions, as shown below. This preserves the periodic structure of time and allows the model to recognize patterns that span the day boundary. Such encoding helps reduce artificial discontinuities in model learning and improves the ability to detect rhythmic trends in load behavior.

$$\sin_h = \sin\left(\frac{2\pi \text{ hour}}{24}\right), \cos_h = \cos\left(\frac{2\pi \text{ hour}}{24}\right)$$

2.2.3 Lagged Demand

Previous hour's load (lag1_t) and previous day's same-hour load (lag24_t):

$$\text{lag1}_t = \text{load}_{t-1}, \text{lag24}_t = \text{load}_{t-24}$$

Residential electricity usage often exhibits strong autocorrelation, past consumption patterns are informative about near-future demand. To leverage this, the load from the previous hour (load_{t-1}) and the same hour one day earlier (load_{t-24}) were included as features. These allow the model to recognize both short-term dependencies and consistent daily routines. For example, if a user typically runs heavy appliances around 7 PM every day, the algorithm helps the model anticipate that behavior.

2.2.4 Rolling Mean

Average load over the past 24 hours (roll24_t):

$$\text{roll24}_t = \frac{1}{24} \sum_{i=t-24}^{t-1} \text{load}_i$$

This feature helps reduce the influence of short-term noise and highlights gradual shifts in usage behavior (Zivot et al., 2003). This can include behavior such as increased base load due to seasonal appliance use or changes in occupancy. Rolling averages can help the model distinguish between isolated spikes and more sustained trends, which is particularly useful in reducing overreaction to outlier values.

2.2.5 Temperature

Current and prior hours' temperature are used to reflect weather-driven shifts in demand. Residential electricity usage is often sensitive to ambient temperature, particularly due to heating and cooling systems.

2.3 Random Forest

Random Forest (RF) is an ensemble learning method based on the principle of bagging (bootstrap aggregation). It constructs many decision trees, each trained on a random subset of the data and a random subset of features (Li et al., 2018). Each tree produces an independent prediction, and the final output is found by averaging these predictions.

The approach reduces variance compared to a single decision tree, making it more robust to overfitting and noise in the data. Random feature selection at each split ensures model diversity, which further improves generalization. In the context of electricity demand forecasting, Random Forests are capable of modeling complex, nonlinear relationships between temporal, environmental, and historical consumption features without requiring extensive preprocessing or feature scaling.

RF was selected because it is robust to noise, requires minimal feature preprocessing, and offers strong interpretability through feature importance analysis. By comparing performance between boosting and bagging, the study ensures a fair evaluation of ensemble learning strategies for load forecasting and peak demand management.

Table 1. Parameters used for the RF model

Parameter	Description
Number of trees	100
Maximum depth	5
Minimum number of samples required to split an internal node	2
Minimum number of samples required to be at a leaf node	1
Feature subset	square root of total features per split
Bootstrap sampling	enabled
Random state	0 for reproducibility

2.4 Histogram-Based Gradient Boosting Regression

Histogram-Based Gradient Boosting Regression (HGBT) is an ensemble machine learning technique that builds a strong predictive model by combining multiple weak learners, typically decision trees, sequentially. The forecasting model plays a critical role in enabling the scheduling of generation and storage resources, which improves operational efficiency and minimizes line losses (Guryanov, 2019). HGBT was selected as a forecasting model because boosting methods are particularly effective for time-series regression with tabular data. Unlike linear models, which assume fixed relationships, boosting iteratively reduces residual errors, enabling it to model nonlinear interactions such as the total effect of temperature, time of day, and lagged demand. The histogram-based implementation was chosen because it is very efficient computationally, as it represents continuous features into bins, which allows for faster training without a loss in predictive accuracy. This made it especially well-suited for handling the engineered feature set while delivering high-resolution peak demand forecasts.

Table 2: Parameters used in the HGBT model

Parameter	Description
Maximum iterations (trees)	100
Maximum tree depth	5
Learning Rate	0.1
Random state	0

The first 80 percent of the dataset was used for training and the remaining 20 percent for testing, ensuring that performance metrics reflected true generalization to unseen data.

2.5 Dispatch Optimization

Following load prediction, the HGBT model simulates real-time dispatch of two generators and one battery to meet demand at the lowest cost. The generators are rated at 80 kW and 60 kW, respectively, and are dispatched in a merit-order fashion. The cheaper unit is used first, and the second is only engaged when demand exceeds the capacity of the first. Simultaneously, a small battery is used, and it charges during low-demand hours and discharges during peaks, shaving the highest spikes and smoothing overall generation. Battery flow is defined by:

$$b_t = \begin{cases} -\min(P_{b,max}, \frac{SOC_t}{\eta}) P_{d,t} & P_{d,t} > 75 \\ \min(P_{b,max}, (E_{max} - SOC_t / \eta)) P_{d,t} & P_{d,t} < 40 \\ 0 & \text{otherwise} \end{cases}$$

Effective demand becomes:

$$P_{d,t}^{eff} = P_{d,t} - b_t$$

Generation is then allocated by:

$$(p_{1,t}, p_{2,t}) = \begin{cases} (P_{d,t}^{eff}, 0) & P_{d,t}^{eff} \leq 80 \\ (80, P_{d,t}^{eff} - 80) & 80 < P_{d,t}^{eff} \leq 140 \\ (80, 60) & P_{d,t}^{eff} > 140 \end{cases}$$

2.6 AC and DC Line Loss Modeling

To compare alternating current (AC) and direct current (DC) transmission efficiency, the HGBT model calculates line losses using Ohm's law (Henry, 1992). First, the total current is estimated by:

$$I_t = \frac{\rho_{1,t} + \rho_{2,t}}{V_{rms}}$$

Then, losses are computed separately for DC and AC:

$$P_{loss,DC} = I_t^2 R_{DC}, \quad P_{loss,AC} = I_t^2 R_{AC}$$

Here, $R_{DC} = 0.05\Omega$ and $R_{AC} = 0.06667\Omega$. This accounts for the fact that the skin effect increases resistance in AC transmission. By plotting both DC and AC losses side by side, the script demonstrates why long-distance DC links often carry bulk power more efficiently than AC.

2.7 Feature Importance Analysis

Permutation importance was applied to assess the influence of each input feature. This model-agnostic technique measures the increase in prediction error when the values of a single feature are randomly shuffled, breaking its relationship with the target variable. The analysis was performed using Scikit-learn for both RF and HGBT models to identify dominant predictors and redundant features.

2.8 System Integration

A schematic diagram (Figure 1) summarizes the overall workflow, showing how load forecasting, dispatch optimization, and transmission analysis interact. The figure illustrates the integration of both generators and the battery system feeding a common bus that supplies the residential load.

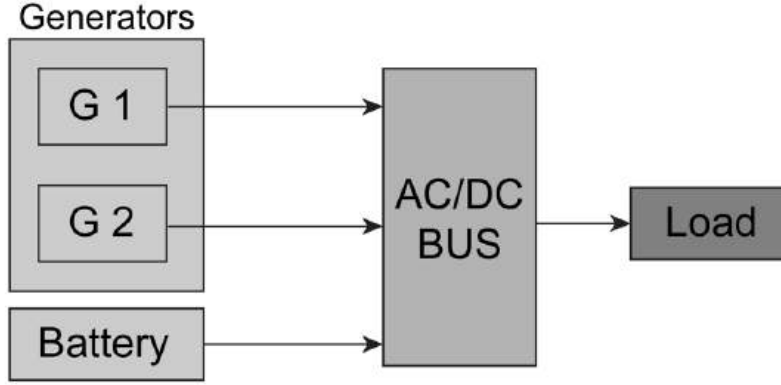


Figure 1. System connectivity diagram: two generators (GEN1 and GEN2) as well as the battery feeding a bus that serves the load. The diagram shows the model used in the simulation.

3. Results

3.1 Model Performance Metrics

There are 3 chosen metrics for model performance: Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and the Coefficient of Determination (R^2). These metrics offer insights into each model's accuracy, precision, and ability to generalize. Both the RF and HGBT models performed relatively well, as they both achieved comparable results in all 3 metrics (MAE, RMSE, and R^2). The RF model slightly outperformed the HGBT model in all 3 metrics. MAE is a measure of prediction error calculated by averaging the absolute differences between predicted and actual values. An important thing to note is that MAE considers all errors equal, so the interpretation of the average prediction error is quite straightforward. MAE is calculated as such:

$$MAE = \frac{1}{n} \sum_{i=1}^n |y_i - \hat{y}_i|$$

Here, $\hat{y}_i$ is the forecasted load and y_i is the observed load.

The Random Forest model achieved an MAE of 4.276, indicating that its predictions deviated from actual demand values by just over 4kW. This level of error is relatively small given the simulated dataset's range and variability, suggesting that RF was effectively able to grasp the dominant load patterns. The Histogram-Based Gradient Boosting model recorded a higher MAE of 4.734, meaning that its average deviation was approximately 0.5 kW greater than RF's.

3.1.1 Root Mean Squared Error (RMSE)

RMSE measures the square root of the average squared differences between the observed (y_i) and predicted ($\hat{y}_i$) values. RMSE and MAE vary because RMSE treats errors based on the degree of the error. For example, a larger error is penalized heavily than a smaller error. This sensitivity is particularly useful in forecasting loads, where extreme values often correspond to

critical events. A lower RMSE indicates better predictive performance. RMSE is calculated as such:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2}$$

Here, $\hat{y}_i$ is the forecasted load and y_i is the observed load.

The RF model achieved an RMSE of 5.421. This value indicates that large deviations from actual demand were quite rare, and when they occurred, they were not extreme, as this RMSE value is relatively low. On the other hand, the HGBT model achieved an RMSE of 5.916, approximately 0.6 kW higher than RF's.

3.1.2 Coefficient of Determination (R^2)

R^2 measures how well a statistical model fits the data. It represents the proportion of variance in the dependent variable that is explained by the independent variables in the model. R^2 is calculated as such:

$$R^2 = 1 - \frac{SS_{RES}}{SS_{TOT}} = 1 - \frac{\sum_i (y_i - \hat{y}_i)^2}{\sum_i (y_i - \bar{y})^2}$$

Here, SS_{RES} is the Sum of Squared Regression, or the variation explained by the model. SS_{TOT} is the Sum of Squared Total, or the total variation in the data. Also, y_i is the observed load, $\hat{y}_i$ is the forecasted load, and $\bar{y}$ is the mean load.

The RF model achieved an R^2 value of 0.937, meaning that it explained approximately 93.7% of the variance in the demand values. However, the HGBT model produced an R^2 value of 0.925, meaning that it explained about 92.5% of the variance in the demand values.

3.2 Feature Importance

Feature importance analysis between the RF and HGBT models reveals which predictors were dominant and the extent to which they contributed to STLF accuracy.

3.2.1 Random Forest Feature Importance

In the RF model, the most influential predictor was the sinusoidal change of hour-of-day ($\sin\_h$), with an importance mean of 4.591. This confirms that the model heavily relied on using the cyclical daily load profile that was put in the synthetic dataset. RF was able to model smooth daily patterns through the wrap-around from 23:00 to 0:00. The second most important feature was the current temperature (temp0), with an important mean of 4.0454. The third most important feature was the hour-of-day (hour), with an importance mean of 1.138.

Lower-ranked features that still positively contributed include the previous hour's load (lag1) and previous hour's temperature (temp1). Interestingly, the rolling 24-hour average (roll24), day-of-week (dow), and $\cos\_h$ all had negative importance means, suggesting that in

RF's ensemble structure, these features may have introduced small amounts of noise or redundancy.

3.2.2 Histogram-Based Gradient Boosting Feature Importance

In the HGBT model, the feature importance distribution was more extreme. `sin_h` again had the highest importance mean, this time being 8.54, which is nearly double its relative influence compared to the RF model. This heavy reliance suggests that HGBT was even more dependent on cyclical encoding. The second most important feature was the hour-of-day (`hour`), with an importance mean of 7.58. This is possibly due to its tree-splitting logic preferring discrete intervals tied to human activity schedules. The third most important feature was the day-of-week (`dow`), with an importance mean of 0.024. While it was negligible in the RF model, HGBT likely detected small but consistent weekday-weekend differences in load, unlike the RF model. Current temperature (`temp0`) had zero measured importance in HGB's permutation analysis. This could be due to the collinearity between temperature and time of day in the dataset. HGBT may have learned the temperature effect indirectly through `sin_h` and `hour`. Both lag-based features (`lag1`, `lag24`) had negligible importance means, with each achieving 0.013496 and -0.068910, respectively. This suggests that HGBT relied less on past load values and more on immediate factors. The rolling average (`roll24`) and `cos_h` both once again showed negative importance, indicating that they were overall not useful in predicting loads.

3.3 Load Forecast Accuracy

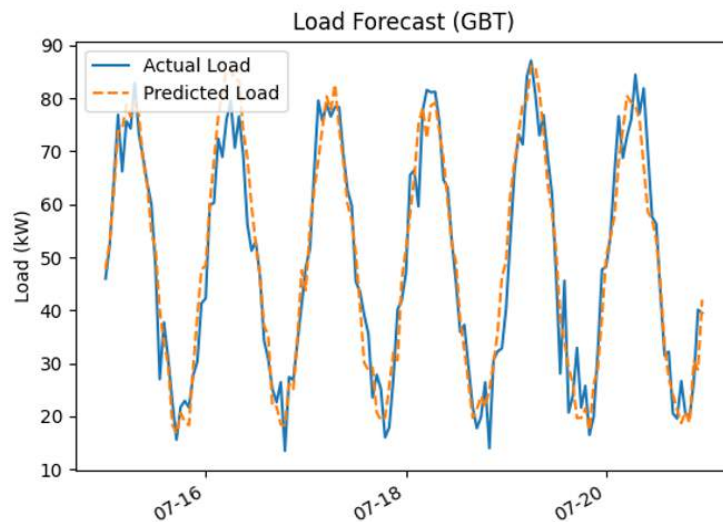


Figure 2. Comparison between actual load and predicted load.

The load forecast produced by the Histogram-Based Gradient Boosting model shows a strong alignment between the predicted load and the actual measured load over the multi-day test period. The model successfully captures both the daily load cycle and the amplitude of peak and trough periods, with only minor deviations at certain peak transitions.

3.4 AC vs. DC Transmission Loss Comparison

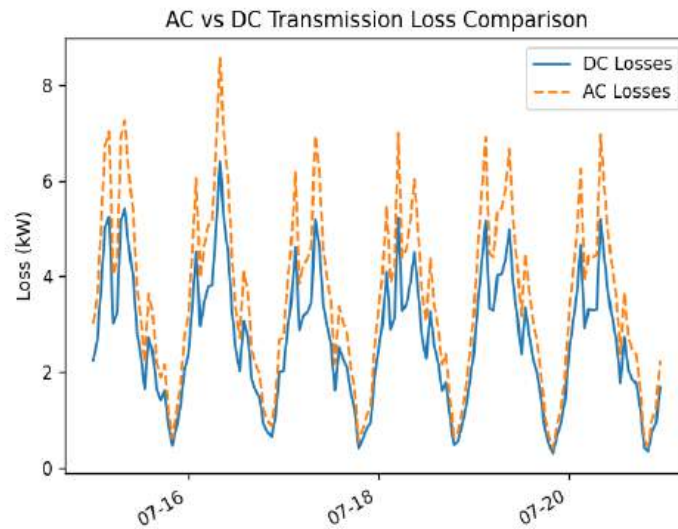


Figure 3. Power loss comparison between an AC-based system and a DC-based system over a total duration of 6 calendar days.

The transmission loss comparison between AC and DC systems highlights consistently lower losses for DC transmission across the entire study period. While both profiles exhibit similar temporal patterns, DC losses are systematically below AC losses during most peak intervals.

3.5 Generator Dispatch and Battery Operation

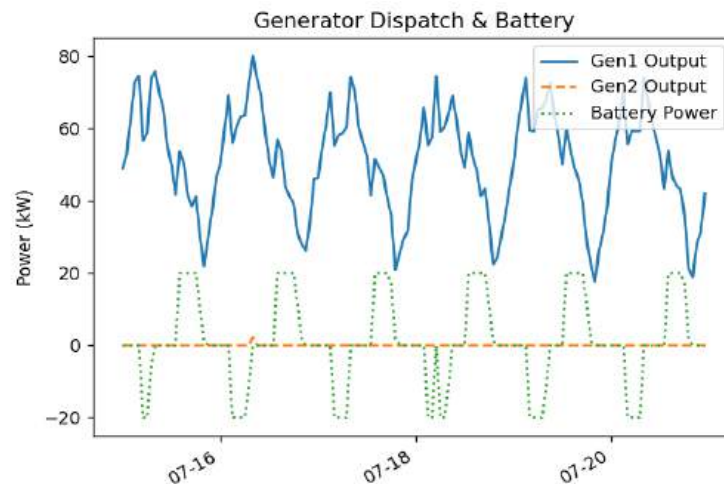


Figure 4: Comparison between generator output and battery power

The generator dispatch and battery power flow analysis reveals that Generator 1 bears the majority of the generation load, while Generator 2 remains largely unused under the optimized dispatch schedule. The battery exhibits a clear charge-discharge cycle, absorbing excess generation during low-load periods (positive power) and supplying energy during peak demand periods (negative power).

4. Discussion

4.1 Summary of Key Findings

The results indicate that RF and HGBT provide strong performance for residential STLF. Predictions accurately captured day-ahead load cycles and peak amplitudes, enabling downstream applications such as battery scheduling and demand-side management. Similar conclusions have been reported in previous comparison studies, in which random forest and gradient boosting consistently ranked among the highest-performing approaches for building and residential load forecasting. This advantage arises because residential load patterns exhibit high randomness and frequent short spikes. RF's bagging mechanism reduces variance and smooths predictions, while HGBT tends to chase residuals and may overfit to short-term noise (Koukaras et al., 2024; Muqtadir et al., 2025).

Permutation importance ranked lagged demand and cyclical time encodings as the most significant features, while temperature showed varying importance across forecasting horizons. This finding aligns with earlier studies emphasizing the combined effect of occupancy-related variables and weather on residential load profiles (Forootani et al., 2022; Muqtadir et al., 2025). Integration of the forecasts into dispatch simulations demonstrated effective peak shaving, consistent with residential demand response systems in which accurate forecasting supports the shifting or reduction of load during high-demand periods (Harikrishnan et al., 2025).

Transmission loss analysis further highlighted that reducing peaks at the distribution level can yield upstream benefits. High-voltage direct current (HVDC) transmission consistently demonstrated lower line losses than alternating current (AC), particularly during periods of heavy loading, confirming results from earlier techno-economic research (Pfeifenberger, 2025; Chenari et al., 2016).

This research provides a direct, head-to-head comparison between bagging (RF) and boosting (HGBT) ensembles for domestic STLF using a standardized feature set. Previous work often compared only subsets of boosted learners or relied on extensive preprocessing; the value of this study lies in isolating the performance differences between ensemble paradigms under minimal preprocessing conditions (Muqtadir et al., 2025; Koukaras et al., 2024). Another notable contribution is the inclusion of permutation importance, a model-agnostic technique that estimates the effect of each feature on predictive accuracy. This method is less common in STLF research, which typically relies on split-gain metrics. Prior literature supports the stability and interpretability of permutation importance for ranking feature relevance (Molnar, 2024). Furthermore, the results demonstrate how predictive accuracy translates into operational value by

enabling optimized battery dispatch for peak load mitigation. This reinforces the growing recognition that forecasting should be evaluated not in isolation, but in the broader context of demand response and home energy management systems (Harikrishnan et al., 2025).

A key strength of this approach is its transparency. The use of two widely adopted ensemble models, validated across multiple error metrics and complemented by permutation-based feature analysis, aligns with best practices in residential STLF research (Muqtadir et al., 2025). Operational relevance was also established through realistic and easily implementable demand-side parameters, demonstrating the practical value of predictive precision in reducing peak loads. Such combined forecasting-and-control frameworks have been emphasized in demand response studies, where integrating forecasting with decision logic enhances overall system effectiveness (Harikrishnan et al., 2025). Finally, linking distribution-level improvements to transmission efficiency provides a novel perspective. The reduced losses and enhanced controllability of HVDC systems have been well documented (Pfeifenberger, 2025; Chenari et al., 2016), and the present findings suggest that improved residential forecasting and load management can complement these higher-level infrastructure benefits.

Several limitations should be acknowledged. First, the dataset lacked detailed residential predictors such as appliance-level signatures and occupant behavior, which have been shown to enhance forecasting precision for individual households (Forootani et al., 2022). Second, ensemble models may encounter predictability limits when extended to longer horizons or when forecasting households with abrupt behavioral changes, consistent with research on predictability boundaries (Xia et al., 2025). Third, the demonstrated potential for demand response assumes full consumer participation and behavioral compliance. Prior studies have shown that participation in such programs varies widely and does not scale linearly with incentives (Parrish et al., 2018). Finally, permutation importance provides diagnostic rather than causal insight; correlated features can distort rankings, so caution is necessary when interpreting importance scores for intervention design (Molnar, 2024).

Future work could incorporate richer residential signals such as high-frequency smart meter data, appliance disaggregation, and thermostat event logs to increase robustness (Forootani et al., 2022). Broader benchmarking of ensemble methods against temporal deep learning models, such as LSTMs or temporal CNNs with walk-forward validation, would also clarify their relative strengths across forecasting horizons and data conditions (Muqtadir et al., 2025). Model explainability could be enhanced by combining permutation importance with SHapley Additive explanation values to capture feature interactions, while cross-seasonal stability testing could help identify retraining intervals (Molnar, 2024; Xia et al., 2025). Future studies should also integrate forecasting and control objectives more tightly, using demand response metrics such as peak-to-average ratio or transformer loading directly within model loss functions, as recommended by recent advanced demand response literature (Harikrishnan et al., 2025). Lastly, linking residential-level forecasting with bulk transmission modeling could yield a more

comprehensive understanding of how local peak shaving influences network congestion and HVDC/HVAC efficiency trade-offs (Pfeifenberger, 2025; Chenari et al., 2016).

Conclusion

This study suggests that ensemble machine learning methods, specifically Random Forest Regression and Histogram Based Gradient Boosting Regression, can provide accurate short term load forecasting and support effective peak demand management. Both models performed well, with Random Forest showing slightly better accuracy across all evaluation metrics. Feature importance analysis confirmed that cyclical time features and temperature strongly influence load behavior, while dispatch simulations demonstrated that accurate forecasting enables peak shaving through coordinated battery use and generator scheduling.

The comparison of alternating current and direct current transmission losses also highlighted the broader operational benefits of incorporating forecasting into grid planning. Although this investigation used synthetic data and a simplified dispatch model, the results clearly demonstrate the potential of machine learning to improve reliability, efficiency, and adaptability in smart grids. Future work using real world datasets and more advanced forecasting models can further validate and extend these findings for practical smart grid applications.

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From e4 to d4: An Analysis of Chess Opening Trends Across the Decade By Kavish Daga

1. Abstract

This study examines the change in chess opening preferences among elite online players across two periods. About 7.7 million games were analyzed from the Lichess Elite Database for the two periods - January 2014 to May 2020 and July 2024 to August 2025. The data were extracted from PGN files and processed using Python scripts to identify the most frequently played openings and first moves. The findings show that while the overall hierarchy of popular openings has remained stable, notable shifts have occurred within specific opening families. Amongst the first moves, a few moves for the White accounted for most of the games. These results suggest that elite players continue to rely on classical openings, with only gradual shifts reflecting modern theoretical developments and evolving playing styles. The study highlights how online elite chess remains rooted in tradition while adapting subtly to contemporary trends.

2. Introduction

Chess is a popular strategic board game played on an 8x8 grid by two players with 16 pieces each - eight pawns, two knights, two bishops, two rooks, a queen and a king. The game ends when either player's king is checkmated or a draw occurs. Claude Shannon, known as the father of Information Theory, calculated that there are roughly about 10^{43} different chess positions (Shannon, 1988). This complex nature of the game has made it a subject of study in various fields such as cognitive science, psychology and computer science. Research has also shown that chess expertise is strongly associated with cognitive ability and strategic reasoning (Burgoyne et al., 2016; Charness, 1992; Yang, 2025). Additionally, it can improve problem solving and cognitive abilities in children and may reduce cognitive decline in older adults (Lillo-Crespo et al., 2019; Aciego et al., 2012; Cibeira et al., 2021). This underscores the importance of chess as a game.

A chess game may be divided into three parts - the opening, the middle game and the ending. Out of these three, the opening may be considered the most important, as it lays the foundation for the rest of the game. There are many standard openings - series of moves in the beginning of a game - which the players may learn in order to gain early advantage in the game. These openings have been refined through computer analysis and practice. The opening preference of players may evolve as better chess engines are developed and new lines are discovered.

Studying changes in opening patterns across different periods would provide how players adapt to changing game styles. This study aims to do so by comparing the openings and the first moves played in games played on Lichess – a free, open-source and one of the most popular chess websites – across two different time periods.

3. Method

3.1 Data source

For the study, the data were obtained in the form of PGN (Portable Game Notation) files – a standard form for recording chess games and other metadata – from Lichess Elite Database from <https://database.nikonoel.fr/> which is a database of all games by players rated 2500+ against players rated 2300+ (2400+ against 2200+ before 2022) on Lichess.org, excluding the bullet games. The database is useful to check the latest theoretical novelties as strong players usually test them online. The game data was obtained on a month on month basis for two periods: January 2014 - May 2020 and July 2024 - August 2025. The comparison between the two periods will help us understand the change in opening patterns.

3.2 Dataset Description

Several variables were used from the PGN files to understand the opening behaviour. The [Opening] tag in the PGN file provided with the name of the opening which was used to know the opening family and the specific opening variation played in a game.

The first moves played by the White players and the corresponding first moves played by the Black players were also extracted from the move sequence in the PGN file which stores all the moves of a game in standard algebraic notation, where each move is a letter, representing the piece followed by the square where it being moved. For example, *Nc5* represents a knight moving to the *c5* square. Similarly K denotes king, Q the queen, B the bishop, R the rook and no letter indicates a pawn move. In total, 3,734,750 games from May 2024 to August 2025 and 3,594,940 games from January 2014 to May 2020 were analyzed.

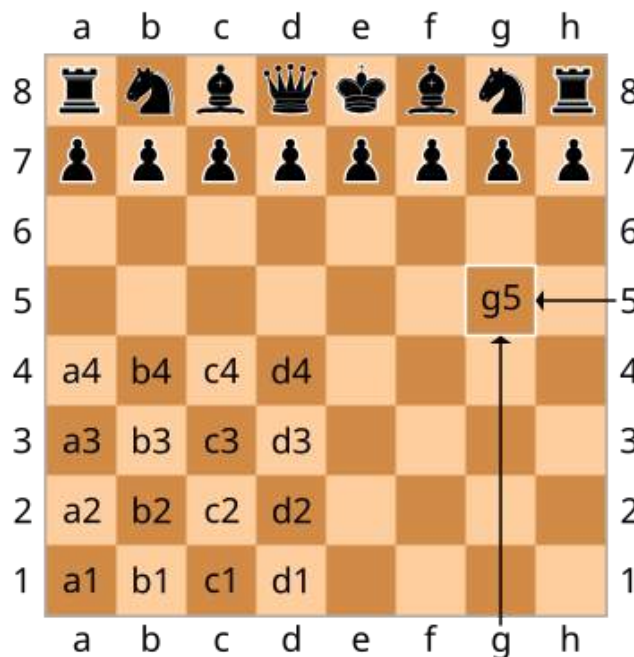


Fig 1: A chess board displaying chess coordinates

3.3 Data Processing

The PGN files were processed using a custom Python script. The count of games for each opening family and the variations under it and for each first move played by White and Black were then saved in an Excel file. The variations under a family were then grouped together (e.g., *Sicilian Defense: Najdorf Variation* and *Sicilian Defense: Classical Variation* were both categorized as *Sicilian Defense*). However, the Excel data was not completely standardized. For example, the *King's Gambit Declined, Classical Variation* and the *King's Gambit Accepted* were mistaken as 2 different families, even though they both were part of the broader *King's Gambit* family. Therefore, with the help of a few additional Python scripts, along with some manual verification, the Excel data was further cleaned and the opening families were classified under broader categories. Despite these adjustments, minor classification inaccuracies may still remain.

4. Results

4.1 Distribution Of Opening Families

During both the periods - January 2014 to May 2020 and July 2024 to August 2025 - nearly all of the top 10 openings from the first period remained in top 10 in the second period too, suggesting that top players prefer to play a handful of stable and known openings. The *Sicilian Defense* continued to dominate in both the periods, accounting for 18.51% of all the games analyzed in the first period and 17.97% in the second one. *Indian Defense* was the second most played opening and remained a trusted choice between top players, accounting for about 13.5% of all the games analyzed in both the periods. The *Ruy Lopez* and the *Queen's Gambit* saw substantial increase in popularity (+1.77 and +2.09 percentage points, respectively) while the *Modern Defense* experienced a substantial decrease (-1.41 percentage points). The *Caro-Kann Defense* and *Zukertort Opening* increased slightly in popularity while the other openings remained slightly stable. Figure 2 shows the data for the top 10 openings by number of games played in either period. The frequency percentages were rounded to two decimal digits for clarity.

Opening name	Frequency (Period 1)	% Frequency (Period 1)	Frequency(P eriod 2)	% Frequency (Period 2)	Change ($\Delta\%$)
Sicilian Defense	665405	18.51	671250	17.97	-0.54
Indian Defense	485645	13.51	503991	13.49	-0.02
English Opening	241539	6.72	260749	6.98	0.26
French Defense	225562	6.27	233560	6.25	-0.02
Caro-Kann Defense	187723	5.22	224471	6.01	0.79
Slav Defense	135720	3.78	130188	3.49	-0.29

Queen's Gambit	128677	3.58	211884	5.67	2.09
Modern Defense	118805	3.3	70609	1.89	-1.41
Ruy Lopez	102873	2.86	173066	4.63	1.77
Zukertort Opening	100680	2.8	128076	3.43	0.63
Italian Game	64274	1.79	82667	2.21	0.42

Figure 2: Distribution of game for various openings for Period 1 (Jan 2014 - May 2020) and Period 2 (July 2024 - Aug 2025)

4.2 Distribution Of First Moves

The majority of the games began with one of the four moves - *e4*, *d4*, *Nf3* and *c4*. Together they accounted for about 95% of all the games analyzed during both the periods, with *e4* and *d4* alone accounting for about 80% of all the games analyzed. Although *d4* is still a very popular choice, it did experience a decrease in popularity (-2.22 percentage points). Meanwhile, *e4* and *Nf3* experienced a slight increase (+1.16 and +1.33 percentage points, respectively). The percentage frequency of other moves remained largely unchanged.

Unlike the first moves played by White, the first moves by Black were more varied and not concentrated to just the top two moves. Although it experienced a slight decline in popularity, *Nf6* remained the most popular response by Black during both the periods, accounting for 26.21% of all games analyzed during the first period and 24.67% during the second. *e5* and *d5* became more popular in the second period (2.55 and 1.2 percentage points, respectively). Meanwhile, *g6*, *d6* and *c5* experienced slight decreases in popularity. Most of the other moves remained equally popular during both the periods.

Figure 3 and 4 show the data for the top 10 first moves by number of games played in either period for White and Black, respectively. The frequency percentages were rounded off to two decimal digits for clarity.

First move	Frequency (Period 1)	% Frequency (Period 1)	Frequency (Period 2)	% Frequency (Period 2)	Change ($\Delta\%$)
e4	1712905	45.24	1802799	46.4	1.16
d4	1318783	34.83	1267105	32.61	-2.22
Nf3	352574	9.31	413276	10.64	1.33
c4	223198	5.89	243251	6.26	0.37
b3	53864	1.42	61269	1.58	0.16

g3	45532	1.2	36925	0.95	-0.25
f4	27051	0.71	18508	0.48	-0.23
Nc3	22688	0.6	13609	0.35	-0.25
e3	16593	0.44	15621	0.4	-0.04
d3	13138	0.35	13097	0.34	-0.01

Figure 3: Distribution of games for various first moves by White

First move	Frequency (Period 1)	% Frequency (Period 1)	Frequency (Period 2)	% Frequency (Period 2)	Change (Δ%)
Nf6	984268	26.21	951257	24.67	-1.54
c5	782956	20.85	774338	20.08	-0.77
d5	568919	15.15	630306	16.35	1.2
e5	419848	11.18	529251	13.73	2.55
e6	323104	8.6	333416	8.65	0.05
c6	229209	6.1	261301	6.78	0.68
g6	181840	4.84	143397	3.72	-1.12
d6	174840	4.65	149863	3.89	-0.76
f5	46905	1.25	36474	0.95	-0.3
Nc6	44098	1.17	46364	1.2	0.03

Figure 4: Distribution of games for various first moves by Black

5. Discussion

5.1 Trends in Chess Openings

The analysis of opening preferences across the two periods reveal that the choice of most of the elite players remained quite stable over the time. The majority of the top openings from the first period also remained the top openings in the second period. This suggests that while new theoretical ideas and novelties continue to emerge, the fundamental opening repertoire of elite players favours the more classical and traditional systems.

Openings such as the *Sicilian Defense* and *Indian Defense* maintained their top positions

across the period, suggesting that elite players prefer the theoretical depth and the sheer flexibility that these openings provide. The slight increase in *English opening* and *Ruy Lopez* suggest an increasing trend of flank openings by the White. The increase in the popularity of *Queen's Gambit* is also an interesting one. This trend may reflect a broader shift among elite players towards openings that balance solidity with flexibility. Meanwhile, decline in the *Modern Defense* could imply a gradual preference for systems offering clearer structural plans and a reduced risk of early tactical imbalance.

5.2 Trends in First Moves

The distribution of White's first moves remained mostly concentrated to *e4* and *d4*. Along with *Nf3* and *c4*, these four moves account for roughly 95% of all games analyzed. This stability in the concentration of these moves show that the elite players prefer a few moves only which quickly facilitate development and central control. However, a slight decline in popularity of *d4* (-2.22 percentage points) and a slight increase in the popularity of *e4* and *Nf3* (+1.66 and +1.33 percentage points, respectively) highlight the shift towards a more flexible approach and an attempt to avoid deeply analyzed or forced *d4* lines.

The distribution of Black's first moves was more varied and spread across a few more moves than White. There was an overall modest but noticeable change for the preferred first response by Black. The rise in preference of *e5* and *d5* point towards a growing interest towards more classical openings which contest for centre directly. Conversely, the decline in popularity of moves such as *Nf6*, *c5*, *g6* and *d6* may show that players are moving away from hypermodern openings.

5.3 Limitations

While the study provides a comprehensive analysis of opening patterns, several limitations still exist. Although more than three million games were analyzed for both the periods, the data was extracted from Lichess Elite Database which only includes online games between players rated 2500+ and 2300+ (2400+ against 2200+ before 2022) on Lichess, excluding the bullet games. Therefore, the data might not generalise to lower-rated players or over the board play. Additionally, even though the classification of families was done carefully, some insignificant minor errors like a misclassification may remain. The data used in the study didn't include the games between the two periods i.e, June 2020 - June 2024 which would have helped better understand the transition of opening trends between the two periods. Lastly, while the analysis focussed on the first moves to analyze the change in open patterns, it does not take in account deeper move sequences which could give us an even clearer image of the opening trends.

6. Conclusion

The study analyzed changes in opening trends by analyzing over 7 million games played on Lichess between 2 periods - Jan 2014 to May 2020 and July 2024 to Aug 2025. The results

show that while most of the top 10 openings by number of games played in period 1 remained in the top 10 in period 2 too, there were some notable changes among them too. The *Queen's Gambit* and *Ruy Lopez* have gained popularity, whereas openings such as the *Modern Defense* experienced a decline.

The analysis on first moves showed that while the first moves by White largely remained concentrated to a few moves, the first move by Black varied over more moves. The analysis also showed elite players are favoring moves which lead to a more flexible play.

Overall, the findings indicate that while the fundamental opening repertoire of elite chess players remains consistent, evolving player preferences and modern theoretical developments continue to shape subtle yet significant change in opening patterns.

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Fair and Explainable Machine Learning for Autism Diagnosis By Eunseo Whaong

Abstract

The detection of Autism Spectrum Disorder (ASD) has seen significant improvements since the integration of machine learning (ML) into its diagnostic practices. Traditionally, the diagnosis of ASD is a complex and resource-intensive process that requires clinical expertise and time-consuming behavioral assessments. In recent years, however, ML has become a promising tool to support early ASD diagnosis by identifying subtle patterns in behavioral and clinical data. Still, despite its benefits, ML models face two critical challenges in healthcare: ensuring fairness and providing interpretability.

In this study, we investigate the application of machine learning techniques to ASD diagnosis using a dataset from the UCI Machine Learning Repository. We focus on three popular classification models to build predictive models that can diagnose ASD with high accuracy: Logistic Regression, Random Forest, and XGBoost. Using these models, we build predictive models that are capable of diagnosing ASD with high accuracy. Beyond standard performance metrics like accuracy, precision, and recall, our analysis emphasizes two critical aspects in healthcare ML applications: fairness and explainability.

Fairness analysis will be conducted to assess whether the models exhibit bias across sensitive attributes like gender. Disparities in predictive performance or error rates across these groups indicate algorithmic bias which we quantify and address. Additionally, we integrate Explainable AI (XAI) technique SHapley Additive exPlanations (SHAP) and Local Interpretable Model-agnostic Explanations (LIME) in order to interpret the model's decisions. By examining the contribution of each feature to individual predictions, SHAP and LIME provide transparency of the functions of the models, facilitating greater trust in automated ASD diagnoses.

This study demonstrates not only the predictive power of ML models in ASD detection but also highlights the necessity of embedding fairness and interpretability into deployment.

Introduction

Autism Spectrum Disorder (ASD) affects an estimate of 1 in 31 8-year-old children in the United States and is more than three-times as common in boys than it is in girls (National Institute of Mental Health, 2023). Early diagnosis is strongly associated with improved developmental outcomes, yet today's standard diagnostic practices, like behavioral assessments conducted by clinicians, remain time-consuming, resource-intensive, and inaccessible worldwide (Rasul et al., 2023). These constraints motivate the search for simple but effective screening tools that can flag high-risk individuals for definitive evaluation.

Over the past decade, machine learning (ML) methods have emerged as a promising addition to traditional ASD screening, performing accurate diagnoses that rival long trusted clinical instruments such as behavioral questionnaires and motion analysis (Perochon et al., 2023; Simeoli et al., 2024). This study shows that the basic ML classifier can perform well on publicly available traditional ASD screening questionnaires with data maintaining fairness and

interpretability. Publicly available datasets such as the UCI “Autistic Spectrum Disorder Screening” corpora for children and adults, each of which contain responses to the ten-item Autism-Spectrum Quotient (AQ-10), have become common benchmarks for these algorithms (Thabtah 2017a; Thabtah 2017b). Despite the encouraging headline metrics of emerging use of technology in ASD detection, two issues currently limit clinical adoption: Fairness and Explainability.

Fairness: Models trained on historical data can amplify disparities, yielding systematically different error rates across features like age, gender, ethnicity, or other attributes. In healthcare especially, such biases threaten to widen existing inequities in access and care quality.

Explainability: Clinicians and caregivers are understandably reluctant to trust “black-box” predictions, especially when the results could affect a child’s long-term development. Transparent explanations are therefore essential for accountability, clinical validation, and shared decision-making.

In this study, both challenges are addressed. Using the combined UCI child and adult AQ-10 datasets, we construct three widely-used classifiers: Logistic Regression, Random Forest, and XGBoost. Beyond conventional performance measures like accuracy, precision and recall, we quantify algorithmic fairness by focusing on gender as a sensitive attribute, and provide model transparency through SHAP for global and LIME local feature attributions for each instance.

The results show that high predictive accuracy can coexist with minimal gender performance gaps and clinically intuitive explanation profiles. This suggests a practical way to use ML for reliable and fair ASD pre-screening. More broadly, this study illustrates how fairness auditing and explainable ML can be used in healthcare to make prediction tools more useful and responsible.

Data and Methodology

The data that this study utilizes are the combination of two public ASD screening datasets from the UCI repository: the Child dataset (for ages 4-11) (Thabtah 2017a) and the Adult datasets (ages 18+) (Thabtah 2017b).

Before modeling, the data are preprocessed for missing value handling, cleaning the values by identifying duplicates, applying one hot encoding for categorical values, utilizing min-max scaling for numerical values, following standard approaches in the machine learning process (Geron, 2022).

Data Acquisition and preparation

Each dataset contains responses to the Autism Spectrum Disorder screening questionnaire, which comprises 10 binary questions (score 1 from behavior indicative of ASD, 0 otherwise) and additional demographic information. There are 292 instances for children datasets

and 704 instances for adult datasets with 20 features and 1 target. Table 1 summarizes the dataset characteristics.

Variable Name	Role	Type	Demographic	Missing Values
A1_Score	Feature	Integer		no
A2_Score	Feature	Integer		no
A3_Score	Feature	Integer		no
A4_Score	Feature	Integer		no
A5_Score	Feature	Integer		no
A6_Score	Feature	Integer		no
A7_Score	Feature	Integer		no
A8_Score	Feature	Integer		no
A9_Score	Feature	Integer		no
A10_Score	Feature	Integer		no
age	Feature	Categorical	Age	yes
gender	Feature	Categorical	Gender	no
ethnicity	Feature	Categorical	Ethnicity	yes
jaundice	Feature	Binary		no
family_pdd	Feature	Binary		no
country_of_res	Feature	Categorical	Nationality	no
used_app_before	Feature	Binary		no
result	Feature	Integer		no
age_desc	Feature	Categorical	Age	no
relation	Feature	Categorical		yes
class	Target	Binary		no

Table 1 : Detailed overview of ASD dataset

Key features include: A1–A10 scores – binary answers to the screening questions (such as eye contact, interest in social activities, imaginative play, etc.), age, gender (m/f), ethnicity (categorical with values like White-European, Black, Asian, Middle Eastern, etc.), jaundice (whether the individual was born with jaundice - yes/no), family_pdd (whether there is a family member with Pervasive Developmental Disorder (yes/no), country_of_res (the individual's country of residence), used_app_before (whether they have used the screening app before), and relation (who is completing the test). The datasets also provide a derived result (numeric) which is essentially the raw screening score (count of “yes” answers to the 10 questions), and an age_desc field which is a string indicating the age range (e.g., "4-11 years" for all children, "18 and more" for adults).

Before modeling, the data preprocessing was performed as below:

- The “result” column is excluded since it is simply the sum of A1score - A10score which is a redundant feature.
- The questionnaire responses (A1–A10) and other binary yes/no fields are converted to 0/1 values.
- For multi-class categorical features (ethnicity, country, relation), we applied one-hot encoding (creating dummy variables) so that no ordinal relationship is implied.
- Age was left as numeric (for adults, age is in years; for children, age in years as well), then standardized by min-max scaling to [0,1] range.

$$P_{scaled} = \frac{P - \min(P)}{\max(P) - \min(P)} \quad (1)$$

where P represents input values and P_{scaled} is the standardized value.

- The target column “class” was encoded as 1 for YES and 0 for NO.

After encoding, the dataset is splitted into training and test sets (80/20 split) in a stratified manner, ensuring the class ratio is maintained. We used the same split for all models to allow paired comparisons.

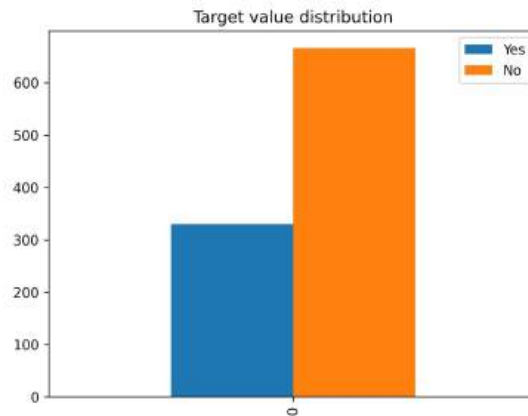


Figure 1 : Data distribution of target column “class”

Modeling

K-fold cross-validation

When training the classification models, K-fold cross-validation technique is used. In a single train-test split, the error measure can be different based on different train dataset. Due to this possible issue, k-fold cross-validation technique divides the training data into k equal groups and $k - 1$ groups are used to train the model then the remaining group is used for validation. This procedure is repeated k times with all possible combinations of training groups. After taking the average of the error metrics from all the k different trainings, the model with the lowest average error score is chosen as the final model. This study uses 3-fold cross validation.

Models

In this study, three supervised learning classification models are trained: Logistic Regression (LR), Random Forest (RF), and XGBoost (XGB), as described in established ML methodology (Geron, 2022).

Logistic Regression is a linear model that produces the probability of a binary outcome as a function of features (“Logistic Regression”, 2025). It estimates the parameters of a logistic model (the coefficients in the linear combinations). Since the data includes questionnaires which could be a strong predictor and the linear model could work very efficiently. The scikit-learn python library’s LogisticRegression implementation is used.

- The logit of the probability of the event that it models is a linear combination of features as below:

$$\log\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_k x_k \quad (2)$$

- The logistic function transform the linear combination into a probability between 0 and 1:

$$p = \frac{1}{1 + e^{-(\beta_0 + \beta_1 x_1 + \dots + \beta_k x_k)}} \quad (3)$$

where p is the probability of the outcomes of interest, $x_1, x_2, \dots, x_k$ are the independent variables, and β_0 is an intercept, and $\beta_1, \beta_2, \dots, \beta_k$ are coefficients.

Random forest is an ensemble learning method for classification and other tasks that works by creating a multitude of decision trees during training (“Random Forest”, 2025). For classification tasks, the output of the random forest is the ASD diagnosis result selected by most trees. It assembles uncorrelated trees using methods like bagging and feature randomization.

Bagging is to use different randomly selected participants of the training set with replacement when training.

Extreme Gradient Boosting(XGBoost) is an optimized gradient boosting library that builds trees sequentially, each one correcting errors of the previous (“XGBoost”, 2025). It is designed for speed, scalability, and high predictive performance, making it a popular choice for both regression and classification tasks, as well as ranking problems. It builds an ensemble of decision trees sequentially, where each new tree corrects the errors of the previous ones by optimizing a loss function using gradient descent.

Hyperparameter Grid Search

To identify optimal model configurations, we performed a grid search over a selected set of hyperparameters for each classifier. Below is a summary of the ranges and choices we used, along with the rationale for each parameter selection:

Logistic Regression

- Penalty: L1(Lasso) and L2(Ridge) regularization are compared. L1 can produce sparse solutions by making weak feature weights to zero, which may be beneficial when many features items are weakly predictive. L2 enforces small-but-nonzero weights on all features, which can improve stability when many of the features carry some level of predictive signal.
- Inverse Regularization Strength (Parameter C) : The hyperparameter $C = \frac{1}{\lambda}$ controls the trade-off between fitting the training data and penalizing large weights. The seven different magnitude (from 10^{-3} to 10^3) were compared from extremely strong regularization to very weak regularization .

Random Forest

- Number of Trees: More trees typically reduce variance but increase computational cost. The number of trees of 600 to 1000 in increments of 200 are compared ensuring that both small and large ensembles were considered.
- Maximum Features per Split: “auto” uses all features at each split, which may lead to stronger but more correlated trees. “sqrt” uses around 10 features per candidate split which is the square root of the total 115 features while “log2” uses around 7 features per split which is $\log_2(115)$.
- Maximum Depth: Deep trees can fully fit the training data but risk overfitting. Shallow trees may underfit. The maximum depth of 230, 340 and 450 are compared.
- Criterion: Decision trees must decide at each node, which feature and threshold to split on so as to best separate the classes. “Gini” and “Entropy” are used to quantify how pure a node is. A node with all samples from one class scores 0. For example, if all participants who answered “YES” to A-4 are actually diagnosed as ASD, that node is perfectly pure with the score 0, while a node with 50/50 mix of two classes (ASD or Not

ASD) scores highest. The best split is the one that decreases impurity or entropy compared to the parent. “Gini” measures the probability that a randomly chosen sample in the node would be misclassified. “Entropy” measures the uncertainty in a node’s class distribution. A node that is perfectly mixed has maximum uncertainty while a pure node has zero uncertainty.

XGBoost

- Maximum depth: The maximum depth of each boosted tree. Lower depths yield simpler trees, higher depths can capture complex interactions but could yield overfitting.
- Number of estimators: Too few trees underfit while too many could overfit.
- Learning rate: The learning rate scales each tree’s contribution. A higher rate (0.1) speeds convergence but risks overshooting the global optimum, a lower rate (0.01) slows learning but can produce more robust models.

The summary of initial parameters and selected parameters after grid search is shown in Table 2.

Model	Initial Parameters	Optimized Parameters
Logistic Regression	penalty: ['l1', 'l2'] C: [0.001,0.01,0.1,1,10,100,1000]	penalty: ['l1'] C: [10]
Random Forest	n_estimators: [600,800,1000] max_features: ['auto','sqrt','log2'] max_depth: [230,340,450] criterion: ['entropy','gini']	n_estimators: 1000 max_features: sqrt max_depth: 230 criterion: entropy
XGBoost	max_depth: [2 - 9] n_estimators: [60,100,140,180] learning_rate: [0.1, 0.01, 0.05]	max_depth: 2 n_estimators: 180 learning_rate: 0.1

Table 2. Grid Search parameters

Performance Metrics

For each model and dataset, we computed standard classification metrics: precision (4), recall (TPR) (5), specificity (TNR) (6), accuracy (7), AUC (Area Under the ROC Curve) and F1-score (8). However, since our focus is on fairness, we paid particular attention to Recall (TPR) and False Positive Rate (FPR) (9) for each subgroup. Specifically, for gender attributes we computed the confusion matrix and metrics for that subgroup.

- Precision: The proportion of True Positive predictions to all positive predictions (both True Positives and False Positives)

$$Precision = \frac{TP}{TP + FP} \quad (4)$$

- Recall or Sensitivity: The proportion of True Positive predictions to all actual positives (True Positives and False Negatives).

$$Recall = \frac{TP}{TP + FN} \quad (5)$$

- Specificity: The proportion of True Negative predictions to all actual negatives (True Negatives and False Positives)

$$Specificity = \frac{TN}{TN + FP} \quad (6)$$

- Accuracy: The proportion of the correct predictions to all predictions.

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN} \quad (7)$$

- ROC-AUC: The receiver operating characteristic (ROC) compares False Positive rate with True Positive rate to measure the ability of the model to distinguish between the classes. The ROC curve plots recall versus 1 - specificity. By comparing the area under the curve (AUC), classifiers can be compared. A perfect classifier will have a ROC-AUC equal to 1, whereas a purely random classifier will have a ROC-AUC equal to 0.5.
- F1 score: F1-score is a combined measure of precision and recall. It is the harmonic mean of precision and recall. Whereas the regular mean treats all values equally, the harmonic mean gives much more weight to low values. As a result, the classifier will only get a high F1 score if both recall and precision are high.

$$F_1 = \frac{TP}{TP + \frac{FN + FP}{2}} \quad (8)$$

- FPR : The proportion of False Positive predictions to all actual negatives (True Negatives and False Positives).

$$FPR = \frac{FP}{TN + FP} \quad (9)$$

Fairness

To assess whether these ASD screening models treat protected subgroups equitably, this study measures two standard fairness criteria: Equal Opportunity and Equalized Odds from Confusion Matrix-based Metrics (Caton and Haas, 2024; Introduction to ML Fairness Metrics, 2022). Both metrics focus on differences in true positive and false positive rates across sensitive groups—in our case, gender.

Equal Opportunity

Equal Opportunity requires that the true positive rate (TPR, also known as sensitivity or recall) should be the same for all groups.

$$TPR_g = \frac{TP_g}{TP_g + FN_g} \quad (10)$$

and then the Equal Opportunity gap as

$$\Delta_{Eopp} = |TPR_0 - TPR_1| \quad (11)$$

Equalized Odds

Equalized Odds extends Equal Opportunity by also requiring equality of false positive rates (FPR) across groups. We compute:

$$FPR_g = \frac{FP_g}{FP_g + TN_g} \quad (12)$$

$$\Delta_{TPR} = |TPR_0 - TPR_1| \quad \Delta_{FPR} = |FPR_0 - FPR_1| \quad (13)$$

A model is said to satisfy Equalized Odds if both $\Delta_{TPR} = 0$ and $\Delta_{FPR} = 0$.

By focusing on Equal Opportunity and Equalized Odds, we directly target the most critical fairness concerns for a medical screening tool—ensuring that true ASD cases are detected at similar rates for all groups, and that non-ASD individuals are not disproportionately misclassified.

Explainable AI

SHapley Additive Explanations (SHAP)

In order to quantify how each feature (e.g., specific survey items or demographic attributes) contributes to the final predictions, we adopted SHapley Additive Explanations (SHAP), a game-theoretic approach for model interpretation (Salih et al., 2025). SHAP calculates a “Shapley value” for each feature with respect to a given prediction, thereby indicating how much that feature shifts the model’s output from a baseline expectation.

A key advantage of SHAP is that it can provide both local (per-sample) explanations and global insights into feature importance:

- Local explanations reveal how each feature influences an individual instance’s prediction (e.g., a particular child’s screening score).

- Global summaries aggregate the Shapley values across samples, illustrating which survey items or demographic factors the model consistently relies on.

Local Interpretable Model-Agnostic Explanations (LIME)

LIME takes a model-agnostic approach to local interpretability. It is an algorithm that can explain the predictions of any classifier or regressor in a faithful way, by approximating it locally with an interpretable model (Ribeiro et al., 2016). This yields feature weights that explain why the model classified a specific individual as ASD vs. non-ASD.

By combining SHAP and LIME, we gain a global perspective (SHAP summary plots) on which features or questionnaire items the ASD screening model deems most influential overall and a local perspective (LIME's per-instance bar charts) on why the model assigned a particular ASD or non-ASD label to a single subject.

Results

The three models are evaluated - Logistic Regression, Random Forest, and XGBoost—on the hold-out test set after tuning via 3-fold cross-validation grid search. All models achieved strong overall performance with good fairness over gender difference. Tables 3–5 summarize the top five hyperparameter selections of each model with a train-set. Table 6 shows the test-set performance of the top hyperparameter selections of each model. Table 7 shows the subgroup fairness by gender. Figures 3-4 present the associated SHAP summary plot and LIME explanations for the first test sample of each model respectively.

After 3-fold CV with grid search, the best models based on accuracy measure are as below:

penalty	C	Accuracy	Precision	Recall	Specificity	F1	AUC
l1	10	1	1	1	1	1	1
l1	1	1	1	1	1	1	1
l1	100	1	1	1	1	1	1
l1	1000	0.9975	0.9927	1	0.9962	0.9963	0.9984
l2	1000	0.9925	0.9783	1	0.9886	0.989	0.9995

Table 3. Grid Search Result of Logistic Regression

n_ estimators	max_ features	max_ depth	criterion	Accuracy	Precision	Recall	Specificity	F1- score	AUC
1000	sqrt	230	entropy	0.9522	0.9458	0.9107	0.9734	0.9278	0.9911

1000	sqrt	340	entropy	0.9522	0.9458	0.9107	0.9734	0.9278	0.9911
1000	sqrt	450	entropy	0.9522	0.9458	0.9107	0.9734	0.9278	0.9911
600	sqrt	230	entropy	0.9497	0.9387	0.9107	0.9696	0.9243	0.9912
600	sqrt	230	gini	0.9497	0.9456	0.9032	0.9734	0.9238	0.9908

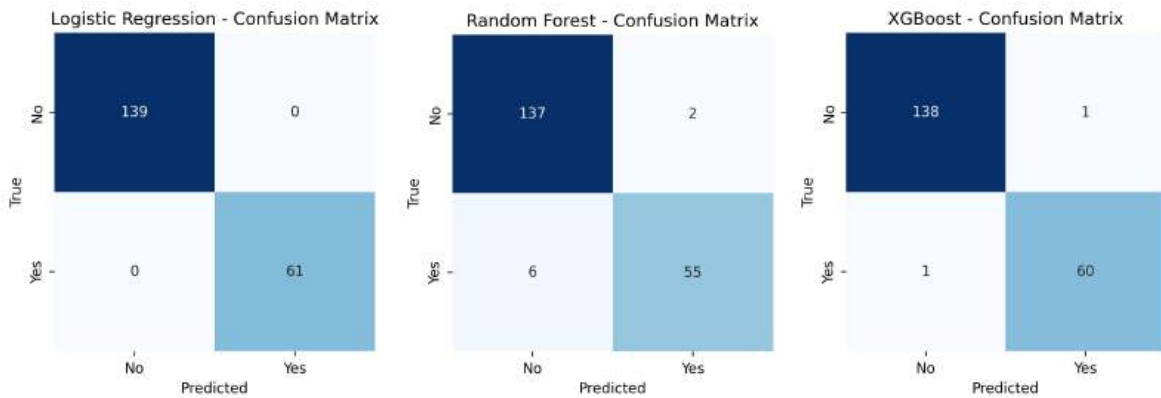
Table 4. Grid Search Result of Random Forest

max_depth	n_estimators	learning_rate	Accuracy	Precision	Recall	Specificity	F1-score	AUC
2	180	0.1	0.9786	0.9773	0.9591	0.9886	0.9681	0.9972
2	140	0.1	0.9774	0.9809	0.9516	0.9905	0.966	0.9969
2	180	0.05	0.9774	0.9847	0.9479	0.9924	0.9659	0.9959
2	100	0.1	0.9723	0.9732	0.9442	0.9867	0.9585	0.9961
4	180	0.1	0.9711	0.9625	0.9517	0.981	0.957	0.9961

Table 5. Grid Search Result of XGBoost

Model	Accuracy	Precision	Recall	Specificity	F1-score	AUC
Logistic Regression	1	1	1	1	1	1
Random Forest	0.9550	0.9643	0.8852	0.9856	0.9231	0.9952
XGBoost	0.9900	0.9836	0.9836	0.9928	0.9836	0.9987

Table 6. Test Data Performance



(a) Logistic Regression

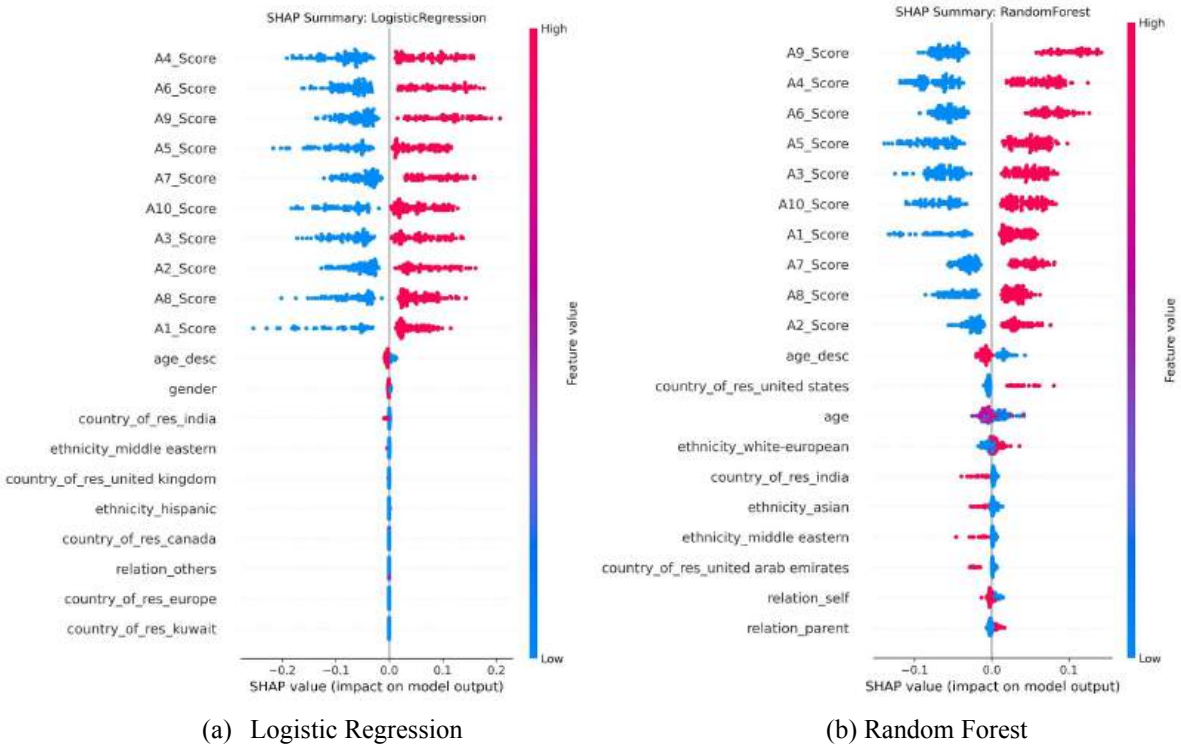
(b) Random Forest

(c) XGBoost

Fig 2. Confusion Matrices for Logistic Regression, Random Forest, and XGBoost showing classification results on the test data

Model	Gender	TPR	FPR
Logistic Regression	Male	1	0
	Female	1	0
Random Forest	Male	0.897	0.018
	Female	0.875	0.012
XGBoost	Male	1	0.018
	Female	0.969	0

Table 7. Fairness across gender showing True Positive Rate (TPR) and False Positive Rate (FPR)



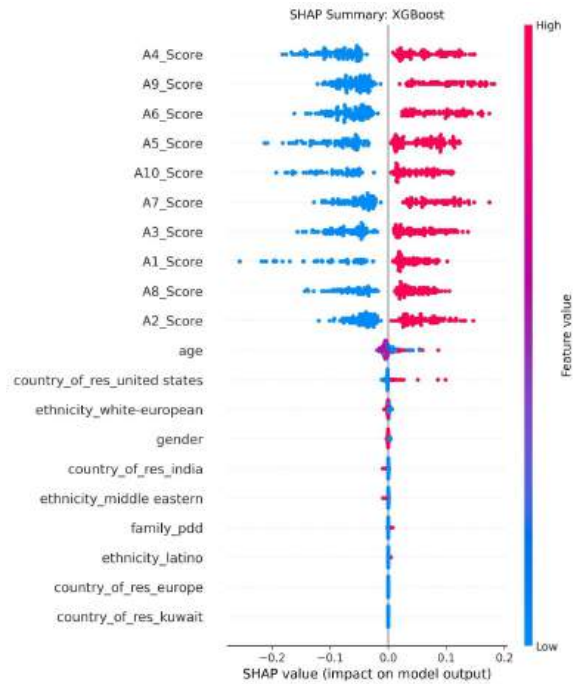
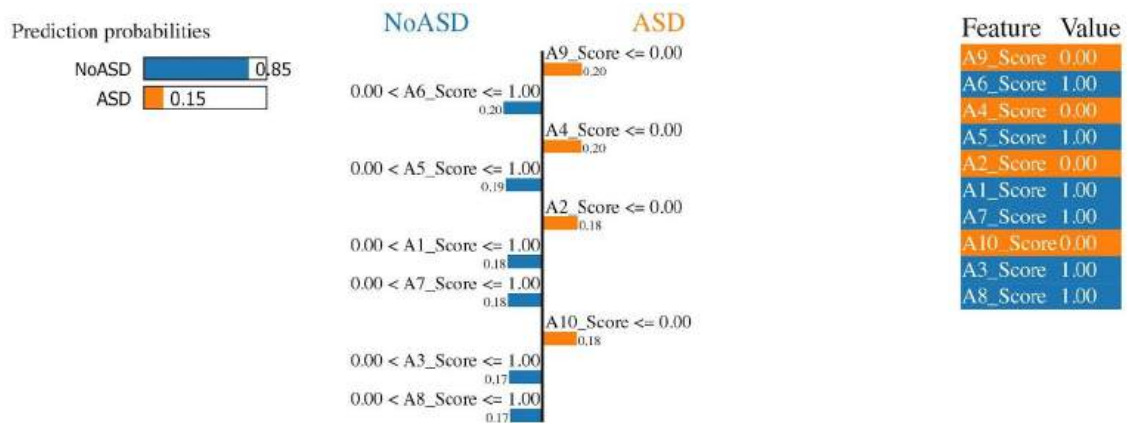


Fig 3. SHAP summary Plot for Logistic Regression, Random Forest, and XGBoost



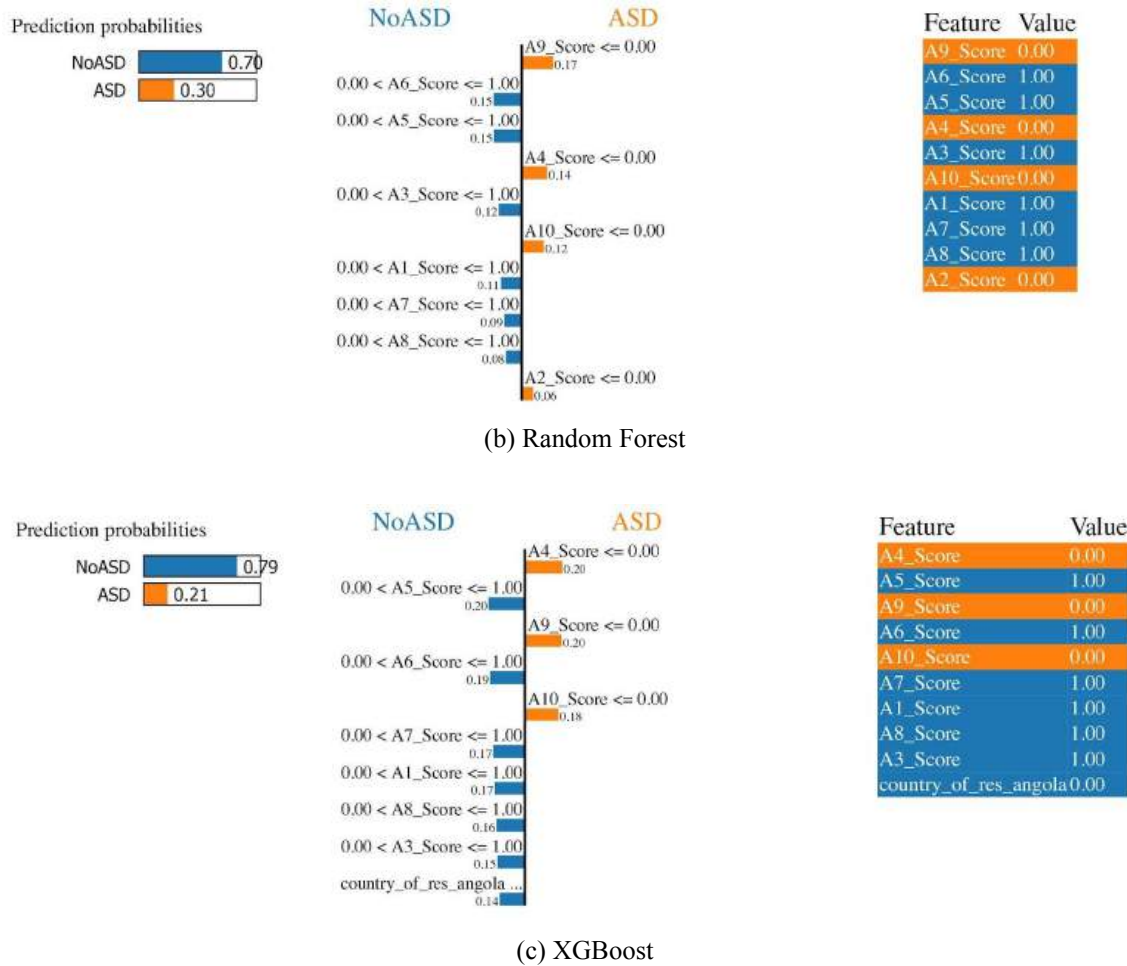


Fig 4. LIME plot for instance index 0 which is identified as non-ASD: Logistic Regression, Random Forest, XGBoost

Discussion

Across all three algorithms, optimized on the same 19-feature screening dataset, we observed logistic regression achieves perfect performance. This suggests a strong linear relationship of the AQ-10 questionnaire items, but this may come for the relatively small dataset. There would be more research with a bigger dataset needed. Random forest and XGBoost performed well with AUC of 0.9952 and 0.9987 respectively. However, recall drops modestly 0.8852 for RF and 0.9836 for XGB indicating a small number of false negatives.

In the fairness analysis, Logistic Regression exhibits no gender difference in both TPR and FPR. Random Forest shows a small gender gap, with a TPR difference 0.022, FPR difference 0.006, while XGBoost shows a 0.031 TPR gap but 0.018 FPR. All three models show good fairness across different genders. This analysis was limited to gender, as subgroup counts for ethnicity and country were too sparse for reliable inference. Future studies with a bigger dataset should expand fairness assessments.

Explainability analysis provided important validation of model behavior. SHAP summary plots revealed that questionnaire items such as A1- 10 were consistently the strongest predictors of ASD. Demographic features (ethnicity, country of residence) contributed negligibly, which both supports fairness and reassures that the models focus on clinically relevant features. In the LIME explanation as shown in Fig. 4, the top contributions for all three models are dominated by AQ-10 questionnaire items, while demographic variables do not appear among the important local features for this test instance. This indicates that, in the local neighborhood of the sample, hypothetical perturbations of questionnaire responses would change the prediction more than demographic variables. Considering together with the SHAP summary plots, these results suggest that our classifiers primarily rely on clinically meaningful questionnaire variables rather than the sensitive demographic features.

Conclusion

This study benchmarked three machine-learning approaches—Logistic Regression, Random Forest, and XGBoost—for early ASD screening using a 19-feature dataset derived from the AQ-10 questionnaire and demographic attributes such as ethnicity, residence, age, gender, etc. All algorithms attained very high discrimination (Area Under the Curve, $AUC \geq 0.9952$), with Logistic Regression achieving perfect metrics, though replication on larger and more diverse dataset is needed to rule out overfitting or dataset bias.

Beyond predictive accuracy, this study incorporated fairness and explainability. Fairness checks by gender revealed minimal disparities in both true positive and false positive rates, suggesting that the models treat male and female participants equitably. Explainable-AI techniques (SHAP & LIME) provided both global and local interpretability, confirming that a small subset of behavioral scores (A1 - A10 scores) drives model output, while demographic factors have negligible influence. These insights align with clinical understanding that core behavioral symptoms are crucial to ASD diagnosis.

However, the relatively small dataset is a limitation, as it constraints models due to overfitting or dataset bias. Future work should test these models on larger clinical datasets to validate these findings, confirm robustness, and extend fairness evaluation to other protected attributes (e.g. ethnicity, country). In addition, integrating multimodal data such as neuroimaging or genetic profiles may produce richer predictive signals.

Overall, this study demonstrates that even basic classifiers can achieve accurate, fair, and interpretable results on an ASD screening dataset. These findings suggest that ML models could serve as practical pre-screening tools for ASD diagnosis, reducing diagnostic delays in real-world clinical workflows.

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Ethical and Practical Quandaries for the Development of Artificial Intelligence Models to Predict In-Match Sports Injury

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Abstract

This article examines the viability of AI models as a means of in-game sports forecasting and injury prediction. In particular, it concerns itself with the practicality and growth potential of existing methodologies for AI-based injury prediction and biomechanical analysis and additionally the data requirements posed by each of these methods. Then, it considers AI as a nascent athletic technological advancement and determines the practicalities, both unique to AI and common to other technologies, of its legitimization.

Keywords

Biomechanics; Machine Learning, Athletics; Artificial Intelligence; Sports Forecasting; Sports Modeling; Sports Legitimacy

Introduction

Matchplay of interactive sports involves an enormous number of factors. Today, as well as in the past, the ability to predict sports outcomes—sports forecasting—is prized by athletic organizations. As data supply increases, sports forecasters can use more advanced models which supply more accurate analysis (Wunderlich and Memmert; Kaur et al.). As forecasting reaches greater and greater levels of precision, the possibility of using forecasted matchplay to predict injury in athletes arises. This nascent paradigm could surpass older analysis techniques by being more flexible, performant and accurate.

The likelihood and mitigation of injury in sports have been previously explored with non-generative AI (Bartlett et al.; Van Eetvelde et al.). While less prone to data sparsity, they rely on factors which limit feature depth such that they are insufficient for predicting matchplay. For instance, strategies to gauge loads which involve athlete-based input such as Rate of Perceived Exertion (RPE), though useful, introduce inconsistencies due to individual player factors such as previous experience and performance (Bartlett et al.). Additionally, there is no guarantee that the player will be available to provide timely, accurate feedback during matches. The more timely, accurate and insightful the analysis, the more it is useful for the development and protection of athletes (Kaur et al.). Such is the promise of Big Data and Generative AI in sports analytics.

This article seeks to discuss and categorize the implementations of AI in athletic technique and strategy, considering also the ethical quandaries of a hypothetical GenAI model

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is both ethically and practically feasible for athletics. It first focuses on the application of predictive tool. From this, it seeks to refute or support the notion that a generative AI predictiveAI, both generative and non-generative, on athletes' technique in isolation to determine the bounds of and requirements for analysis. Then, it evaluates the hypothetical efficacy of a GenAI forecasting model based on these bounds. Finally, it compares the requirements and ramifications of the existence of such a model to prior sports technological advancements.

Matchplay Forecasting

Data Availability and Sourcing: Matchplay

Evaluating the risk of injury for a certain player over the course of a match means understanding the loads placed upon them at all times (Bartlett et al.). To do this over the span of a match before a match requires the entire match to be forecasted. Sports forecasting requires data, with sparsity causing forecasters to reduce feature depth or sample size for analysis(Wunderlich and Memmert; Kaur et al.). Whether data is sufficiently available to forecast matchplay with appropriate feature depth determines if a GenAI forecasting tool can exist. Big Data derived from matchplay has potential to be able to satisfy this requirement for data, and has been used to predict certain features of a match in cricket with non-generative AI models (Kaur et al.).

In association football, the advancement of both sensor technology and regulation to implement said technology is a key step to data acquisition for game prediction. The use of sensors which identify physiological and positional data of players, as legalized by FIFA, satisfies a lack of relevant data (Rein and Memmert). Coupled with numerous other advances in data-collection technology, the lack of information to analyze has become, in recent years, less of a concern (Rein and Memmert; Phinyomark et al.). This is because such advances generate high-volume, low-variety and high-rate-of-production information (also known as Big Data). This sort of data promises holistic insight because of its sheer size, if it can be analyzed. Essentially, the implementation of machine learning to analyze this so-called “big data” may allow for unbiased (Rein and Memmert), high-detail forecasting of game events.

The breadth of data collecting in Indian Premier League (IPL) cricket satisfies the above-stated criteria for Big Data (Kaur et al.). Such data has been determined to be unavoidably impactful to professional sports. Taking a number of insights from big data originating from social media related to matches but more importantly from matches themselves opens the way to greater insight. Big Data can be organized via query into features usable by non-generative AI models, with accuracies up to 84%. The feasibility and effectiveness of preparing Big Data for training generative forecasting models remains to be seen. However, larger data sets have proven to be beneficial for granular analysis. Interactive sports such as cricket hold potential for high-efficacy generative sports forecasting.

Nature of Matchplay

The decision-making of other players on the field is highly variable in team sports. The decision-making process of members on the teams at play creates divergent scenarios. The numerous game-states an AI would require to be trained, when coupled with teams' reluctance to provide accurate internal information out of self-interest creates a scarcity of valid data for use in models. A model which is sophisticated enough for these game states would also demand improved training techniques in addition to a vast amount of data. Indeed, the sheer amount of data requires labelling which is generally performed by humans. Unique to sports, especially team sports, there is usually significant subjectivity between experts regarding the underlying causes of in-match events and injuries (Wunderlich and Memmert; Tan). To accurately label data, the resultant divergence in opinion from sports-based subjectivity would need to be normalized with respect to the label of the data. This process necessitates an exponentially larger amount of information, and the normalization itself cannot be fully accurate due to the subjective nature of human labelling. The training of AI is crucial to the efficacy of the final product; faulty or inaccurate models would be less likely to be used to make decisions with the economic and social heft that professional sports often command.

Sparsity, as previously mentioned, can be addressed by reducing feature depth(Kaur et al.; Tan). Producing a viable, accurate tool with a comparatively narrow scope is preferable to producing a tool with a larger scope that fails to function. The training principle of specificity dictates that training tools and routines should pertain to the activity of improvement. Naturally, maximizing specificity often means reducing unnecessary overhead in training. In this case, additional predictive functionality, depending on how the data is presented to the athlete, can reduce the clarity of information and generate confusion. By contrast, simplifying the functionality of a model both improves accuracy, via the simplification of producing that model, and the actionability of the data by improving its clarity. Improving functionality in this manner creates a viable product which is, additionally, lightweight due to the lack of extraneous features. However, an generative AI with insufficient feature depth is prone to incomplete analysis or, worse, hallucination.

However, not all sports include the same divergent scenarios. Sports which provide many controlled factors by requiring primarily closed skills that may also be individual or coactive in nature are thus the most viable for developing predictive AI. In addition, a sport which is highly repetitive would reduce the variance of the data and thus reduce the scope of the prediction. Sports such as archery, track-and-field, swimming, and other sports which are closed, non-interactive activities satisfy these criteria. These sports, due to their qualities, are more conducive to the development of an accurate predictive model. At some point, however, the controlled nature of the sport means it already lends itself to existing models of forecasting rather than a generative AI approach. In this case, there would be no real reason to implement Generative AI. Thus, a balance must be struck in the level of control and interactivity of a sport for Generative AI to be both feasible and effective.

Sources and Nature of Data

Approaches to Gathering Data: Models Used in Training Environments

Given appropriate data, non-generative AI should be able to differentiate injurious movement and non-injurious movement. One notable strategy for quantifying how likely an injury is to occur in the realm of sports is via the use of ground reaction force profiles. The reaction forces of a player's movement are measurable phenomena which offer insight into the smoothness of a player's movements(Ertelt et al.). The time curves were then distributed among three features (amplitude, coefficients and position) via Gaussian distribution. In the same study, a Bayesian Regularization Artificial Neural Network (BRANN) was used with high to very high accuracy (training $R = 0.998$, test $R = 0.902$) to predict the sport which a particular athlete played. This association between force patterns and one sport suggests a convergence in how athletes move. If enough data were to be collected consisting of these attributes as seen in those with 'ideal' biomechanics, the resultant database could be referenced to identify the movement patterns of other athletes as potentially inefficient, among other possible conclusions such as a totally different playing style or an adaptation due to the variation in athletes' abilities to generate force. Additionally, this practice is suggested to be viable at identifying the efficacy of physical therapy – there is a significant difference between dysfunctional and functional force patterns(Ertelt et al.). Ground reaction force profiles are data which must be voluntarily submitted, however, and additionally require special equipment. This poses issues for collecting a significant amount for analysis especially during active match play of many sports, where this may altogether be impossible.

Some current technologies for attaining the data necessary for analysis of mechanics using AI include applications of commercially available motion-capture technology. One of these solutions is 3D GAIT, which is able to return common values of interest in kinesiology such as joint angles and positioning under load (Phinyomark et al.). Due to the limitations of systems such as 3D GAIT, some other studies may opt for player-reported data such as Rate of Perceived Exertion (RPE) in addition to biological metrics such as heart rate.

One such case is found in reducing injury risk by discouraging excessive training load or faulty biomechanics. Researchers sought to address the disparity between how practice regimens are prescribed, through observable, measurable and easily controlled factors such as mechanical load, running distance, etc. and the physiological stress experienced by the human body in response to these measurable factors (Bartlett et al.). The latter of these stresses, the internal load, is the stimulus which allows improvements in fitness. However, internal load is also subject to variables unique to each player. Previously, this internal load was obtained by simply asking the player to rate their perceived exertion during a training session. From this rating, an artificial neural network demonstrated superior efficiency in predicting the internal load given specific parameters for a training session (such as speed, meters run, impacts, etc.) compared to a linear approach (Bartlett et al.). Since injury is incurred with sharp increases in workload compared to that of previous sessions, the demonstrated success of a machine learning model in predicting internal loads for a prescribed training session promises to also be an effective tool for assisting coaches in planning training sessions that improve players' fitness without risking injury from

excessive acute intensity. However, it is important to note that these approaches often require several rounds of data from several training sessions; In this case, the researchers used only RPE (Bartlett et al.) and previous external loads of a workout.

A more granular analysis is offered in the use of 3D GAIT. In contrast to previously described methodology, this implementation of machine learning also employs commercially available motion capture equipment to fully simulate and derive patterns of movement from test subjects (Phinyomark et al.). The resulting data, like that which is acquired from the electronic health record for incidence prediction of pressure injuries, is considered Big Data due to its sheer volume, rate of production and other factors. AI, among other methods, is a candidate in analysis of the resulting gait data. While numerous, there are finite factors to consider when predicting performance in athletics. With enough information, as seen here and the analysis techniques performed with data from the 3D GAIT biomechanics analysis system, even non-generative AI has demonstrated ability supporting the notion that it can more holistically analyze data and identify risk factors compared to traditional methodology (Van Eetvelde et al.).

Similarly to athletes, the stresses placed on surgeons in medicine affect their performance. The medical field has applied sabermetrics to identify intraoperative cognitive load (Norton et al.) and understand the stresses placed on medical students by different teaching styles during operation. However, the medical field differs from sports in that it is much more overtly non-zero sum. As the goal is to maximize and optimize treatment, there is less reason to withhold information. The aforementioned examples of research demonstrate the efficacy of non-generative AI in predicting load and classifying technique in actors (medical students or athletes). However, they also collect their data in a controlled environment; by the principle of specificity in sports testing, their results cannot be generalized to matchplay.

Data to Analyze Technical Improvements

Using AI to improve players' strategic/physical performance is perhaps the most developed application of AI in athletics (Claudino et al.). Among others, basketball, handball and volleyball see research in AI for 'technical and tactical' improvements. These areas are promising for injury prediction. For instance, an 'artificial neural network' was applied to analyze the shot patterns of a free-throw in basketball. This data would be used to improve the efficiency and accuracy of further free throws. Technical improvements, it is worth noting, can also reduce the likelihood of injury by addressing biomechanical dysfunction. The more power can be applied to the ball in a biomechanically sound, efficient way, the less force the player's body will have to produce overall to achieve the same shooting range. Thus, the player's body will experience less force overall. These technical aspects, such as the shooting of a free-throw, are relatively discrete and short-term. Thus, tracking and analyzing them poses far fewer issues than analyzing the relatively large amount of data collected during matches.

Unfortunately, however, analysis via any means including AI in controlled training environments often cannot recreate the environmental information players use to perform techniques (Davids et al.). The biomechanical outcomes can differ as a result, with the

backswing duration of cricket batters differing whether a ball machine or human bowler was used (Davids et al.). The coordination and decision-making of players can include factors, clearly seen or not, of match situations which may differ from data collected during practices where the analysis was performed. Essentially, this isolated method of improving technique might not necessarily translate to match play scenarios due to the coordination involved being different in nature (Davids et al.).

Sports are not played with the same level of interactivity or control. While sports such as track and field and swimming seek to minimize the interference of the presence of other players, team sports such as football, American football and rugby all must also consider the opponent's actions. This becomes imperative in predicting injury, as the decisions of other players diversify the kind of load a player's body experiences. To train an AI on these decisions as well as a player's own to inform them of their injury risk inflates the amount of data collection work needed. Thus, applications which consider such a number of external factors may be of limited use in athletics where certain players will have varying amounts of associated data based on their playtime. Conversely, applications of AI in training require less information and may be more prevalent due to their ease of access. Therefore, applications which are relatively non-invasive and require relatively less specialized equipment are more likely to become prevalent in athletics.

Ethical and Practical Quandaries

Impact on Data Availability

AI, as previously discussed, promises improvements in sports analytics. However, the prolonged use of it generates a number of practicalities.

Approaches for applying AI seek to leverage its ability to learn and apply a large amount of data. For instance, there has been use of a master system, which is trained with the relevant information on its field of choice, to analyze the gait of athletes and deliver corrections. Today, the application of the master system is elevated in LLMs such as ChatGPT and Google Gemini; these models are also trained on an extremely large amount of data and thus can access any knowledge once asked. Such applications in sports would translate most easily to the previously outlined suggestive model of AI use. AI modelling has also found its applications in other fields which seek to predict the outcomes of injury; AI has been used to predict the mortality of certain traumatic injuries(Kang et al.). However, the parity for this application for biomechanics is limited; a scoring system for trauma in locations on the human body was applied for this application as features on which to train the model. Such features would be hard to acquire on biomechanics; the relatively similar and organized tissues of the body are not subject to as many factors as that which would influence how players move during divergent scenarios in sports(Bandara et al.). Furthermore, the many factors of play during sports present a challenge in discerning relevant features for training a model (Wunderlich and Memmert). The resultant questions about attaining training features and regularizing the different biomechanics of players

will be addressed in this section. The nature of withholding information in adversarial sports further deepens this issue.

Information, particularly analytics, holds enormous influence in the outcome of competitions (Grow and Grow). Considering the adversarial nature of athletics, it would follow that teams would be interested in minimizing the performance of other teams' AI implementations. One way to do this, which holds precedence in the guarding of Sabermetrics in baseball via confidentiality agreements such as NDAs (Grow and Grow).

When the state of a match is formed from the decisions of a multitude of people, predicting the performance of a specific person in it would require understanding of these other influences as well. To consider this unrestricted provision of data from otherwise-secretive athletic organizations to be unlikely would be an understatement.

A different approach accounts for the randomness of game-states from a top-down perspective. Rather than factoring in the specific data of influence in a game, one could use a heuristic approach that models the deviance of a player's performance inside the game environment from their average or ideal performance. Such heuristics are already applied in games such as Go and Chess to efficiently predict the desirability of certain positions. Similarly, this approach could be used to arrive at the specific kind of deviation from their average performance which a player is experiencing through a match. A similar application to this would be the tokenization of words performed by AI models such as ChatGPT. Similar to how ChatGPT ascribes dimensions to certain tokens, a hypothetical sports analysis AI could ascribe different types of variances to a specific interaction within a match.

Again, this approach would necessitate sophisticated training. The practice of tokenization and the creation of vector-spaces demands a significant amount of data and would be prone to the same subjectivity issue when labelling data.

Ramifications of Privacy, of Implementation

Non-AI analytics have already begun to use data which may be considered vulnerable. One instance of this is the right to private biometric data given by the National Women's Soccer League (NWSL) via giving athletes the choice to have their data monitored. AI models demand vast amounts of data, with unethical means being applied already to train language models such as ChatGPT. Players' performance in team sports, being highly varying, necessitate a large amount of data which must be obtained systematically and with proper precautions to preserve the right to biological privacy of players.

Adequate availability of data for research in conjunction with protections to the people to whom the data belongs is necessary in the implementation of a predictive model. This criterion is not unique to sports; a similar relationship with data is applicable to healthcare. One key protection is the Health Insurance Portability and Accountability Act (HIPAA) enacted in 1996. The Privacy Rule contained within this act established nationwide standards to the practices of health insurers and clearinghouses. Under the Privacy Rule, any individual can request their health records and direct the release of these records to third parties. Regulation as standardized

and governed as that seen in healthcare is only seen in high levels of professional sports(Rein and Memmert; Grow and Grow). Thus, a predictive model would most easily access the most ethical data from national-level athletes. This, once again, limits the amount of available training information. In addition, a key difference in predicting incidence of injury in interactive team sports is that, in order to accurately model all factors, information from opposing players would also be necessary(Wunderlich and Memmert). Thus, not only are the metrics of the player used, but the data must also be associated with the player themselves for the sake of accurate modeling. Considering players would not be likely to permit the use of their data for prediction in a competitive environment, the deployment of a truly holistic model would be a breach of privacy in these sports.

By contrast, injuries in individual and coactive sports pertain significantly less to the actions of other athletes. In addition to being more viable for model development due to less variance in data, these sports present significantly fewer boundaries to the access of data because the performance and injury incidence rate of any single athlete is generally not impacted by the behavior of other athletes. However, the integration of predictive AI models into any sport presents issues of its own.

As sports AI is implemented, the sharing of strategically meaningful biometric data such as a player's diet, sleep schedule and even mental health information becomes unlikely for teams who desire a competitive edge. However, technological advancements such as this forecasting tool can face roadblocks for regulation due to their ability to alter the barrier to entry of a sport as well as its competitive spirit. AI will require regulation in accordance with the spirit of the sport at hand as well as in its resource demands. This avoids the alteration of sport as entertainment and reduces inequality between organizations and athletes.

For example, Nike and their Alphafly NEXT% racing shoe garnered significant public attention as they were used to run an unofficial marathon in under two hours (Dyer). These prototypes were advantageous due to their use of two carbon fiber plates and a particularly thin foam formulation (PEBA foam branded ZoomX) that enabled the use of a greater volume of foam. These changes enabled the shoe to return significantly more energy and thus improve running economy compared to other distance running options but also significantly increased the price of the shoe. A year later, the Tokyo Olympics enacted running shoe regulations, including a maximum foam thickness and number of plates embedded within the sole. As a result, shoes such as these and the planned-to-launch Viperfly became illegal. As the games were postponed, additional amendments were made to the ruleset including measures to ensure the availability of shoes to non-sponsored athletes for zero cost. Such supershoes continue to be popular, though in less extreme versions. Many of these racing shoes are exceptionally expensive and function for shorter lifetimes. The latter of these shoes, for instance, is only rated for 50 miles of running. The long-term disposability of these shoes as well as their price continues to pose a barrier to entry for runners. The price barrier of this technology coupled with its benefit causes some shoes to be banned today. However, these improvements to shoe technology were not excessive for the sport

and thus could exist with sufficient vigilance. Similarly, generative forecasting could be sanctioned because it, too, demands significant financial investment.

A similar theme of posing restrictions on equipment presents itself in the regulation of technical swimsuits, or tech suits. As drag provides a significant portion of resistive force while swimming, significant energy consumption can be saved via reductions in drag (Chatard and Wilson). The 24% reduction in skin drag of the LZR over the technical suits of its time provided substantial efficiency gains which resulted in 93 broken world records in March of 2008. In 2010, these full-body technical suits were banned. Today, textile-based suits are used, with additional regulations on body coverage.

The Alphafly and the technical suit enjoyed similar levels of dominance in their specific sport, with most athletes using them (Frevel et al.). The factors which determine the legitimacy of a technological improvement in sport continue to be researched today, with models incorporating the representation of this technology and its effect on cognitive perceptions of legitimacy. As technology is bound to bring about change, regulators must continue to ask whether this change is excessive and beneficial for the sport (Frevel et al.). Depending on the initial capabilities of AI injury prediction and their representation, the separation of teams based on access to this technology may be deemed too significant. Furthermore, AI forecasting can influence how athletes and organizations make decisions within matchplay for fear of injury. AI, in the scope of injury prediction, would need to function as a solely suggestive tool that still necessitates the athlete to act on its prediction. In this sense, the performance of an athlete still depends on how adequately they have completed their training.

AI, in its form as a model which predicts injury, may find its ethical place less as a physical aid and more as a complement to existing analytics methodology. Sabermetrics, or the metrics of the Society of American Baseball Research (SABER,) is defined as an analytics solution that answers practical questions concerning, for instance, the advantages of left-handed pitchers against right-handed hitters (Middleton et al.). Additionally, the aforementioned article analyzed the pull factors of baseball sabermetrics which caused the formation of the community as it is seen today. In addition to the Internet and its facilitation of the interaction between disparate Internet communities being a critical factor, certain attributes of a specific tool were highly influential as well (Middleton et al.). For instance, 74% of the experts interviewed cited a strong preference for code examples when deciding whether to use a certain tool. Conversely, 53.7% cited the lack of sufficient code included as a failure in most documentation. These factors both improve the efficacy of AI and make the development of it more accessible. Ensuring that AI is sufficiently accessible for development in these ways, as well as others, is one possible step for regulation of the tool in sports.

Possible Solutions

Considerations must be made as to whether the output of the AI should be a concrete percentage (Rein and Memmert). Also, the right of players to their information must not be infringed upon; the level of information which is accessible by the AI is bounded by ethics. This

directly impacts the possible scope of the model based on available information. Additionally, the role AI plays in an organization's decision making must be considered; AI generally finds use in a suggestive manner, as an aid, rather than being fully relied upon. In this regard, the efficacy of the model in question, which depends on several factors such as the specificity of its output and the extent of its training, affects the role the model plays in organizations. For efficiency's sake, organizations generally aim to minimize resources such as labor (Marcu and Buhaş) and would likely empower a sufficiently powerful model to make more prescriptive decisions. Both cases have shortcomings: if done excessively, the former case can remove authority from an organization's coaches and instead enable the creators of the AI to influence decisions as well as expose teams to erroneous decisions from an imperfect model. In contrast, the latter case could fail to fully utilize the ability of AI to use large amounts of raw data to draw a conclusion and artificially slow the development of the competition. The mediation between these cases is crucial.

Verbosity, or the detail of a model's predictions, comes with its costs. ChatGPT consumed an estimated 4.8 billion liters of water in its GPT-3 generation and continues to use 148.28 million each day. The energy consumption of a system as verbose is significant. Additionally, its training involves an enormous amount of text. Similarly, AI image generation is trained in public works, even those which did not give explicit permission. By contrast, a simpler TensorFlow model can be trained on a home computer. A program for athletics which seeks to predict a player's status at all points during a match process and must be trained with a similarly large amount of training data to LLMs; the "big data" collected can scale up to hundreds of gigabytes in size. Hence, the origins of this data and the costs of running such a model must be considered. One way to mediate for less detailed models or those trained on less data is by a human sanity check in conjunction with AI output, an arrangement which allows for errors to be caught.

It is altogether likely, considering that the scope of a model inversely correlated with its feasibility and ease of deployment, that less powerful models will be the first to be implemented. This allows for the acclimation of athletics to this tool and reduces the risk of it being deemed excessively powerful.

Comparative Discussion

This article considered the possible aids, quandaries and particularities of the implementation of an AI model to predict injury in professional sports. AI is a tool which has already found use in athletics, with its expansion possibly leveraging techniques seen in the medical field. However, this expansion raises issues related to the development of the model due to the scope of the sport in question, the fair and equitable acquisition of data for both training and application. In addition, AI can also provide regulatory issues similar to other technological advancements in sports.

However, reaching a more conclusive answer to the ramifications of AI implementation requires additional insight on a number of topics. These include:

Training for AI and development of specific training techniques

The training of AI and the specific techniques used in athletics directly determine what input is required to develop a viable model. In turn, the input required determines the depth and amount of data which must be gathered. Additionally, the nature of training AI determines the scope-based rate of growth which a model could possess. This rate of growth, as seen in other technological advancements in sports, would affect the regulation and legality of AI.

Regulation of AI as a Technological Advancement

Keeping the nature of sport the same, as previously identified, is a primary concern for regulators in sport. If, for instance, the competitive nature of the sport between communities of varying wealth levels is to remain, the cost of specific technologies is at least worth questioning (Dyer). In this respect, AI models can be highly resource-intensive if used in-house or potentially informationally insecure and competitively disadvantageous if outsourced. Concerns about the nature, or 'spirit' of the sport changing must also be addressed (Dyer); These concerns are often highly subjective and can easily differ between athletic organizations, leading to divergences in the sport itself. For implementation to keep sport relatively uniform, AI must be incrementally integrated. This avoids the controversy which comes with other technologies which have offered, all at once, substantial improvements (Dyer).

Privacy of Athletes and the Distribution of Data in an Adversarial Field

Athletics are different from medicine in that it is inherently competitive. Protecting the privacy of athletes is thus supported by both the ethical systems of many cultures and is also in the interest of organization. Ensuring proper data availability and sufficient verbosity in the model to predict in-match injury becomes more difficult in team, interactive sports due to these reasons. Thus, sports that are coactive are more likely to see AI models develop.

Conclusion

This article defined the basis of a general matchplay forecasting tool based on generative AI, identified limitations in the implementation of generative AI in athletics both unique to it and common to all technological advances. Additionally, it identified various use-cases and a path to implementation for AI. Through this cursory peering into the ethics of AI, the clearest path would be its use in non-interactive sports, where the nature of the competition limits the amount of required data and does not compel any party to share information for accurate prediction. Additionally, expansion into other sports needs to be carefully controlled to allow the competitions to adapt. The potential of generative AI in this field, as previously stated, relies crucially on the relationship between data supply and feature depth in prediction. These practicalities will further affect generative AI's potential as they affect the tool's regulation of professional sports.

Limitations

This article significantly generalizes the role and needs of AI, ascribing to it a demand for data similar to modern large language models such as ChatGPT. Thus, the informational demands of it may be overstated. Additionally, it presumes that AI models will be a substantial improvement over existing predictive techniques and additionally predict injury with a safety factor that accounts for an athlete's mental state. Thus, there may be greater ramifications to the prolonged implementation of AI than those explored in this article.

Future Research

Relating, in a speculative manner, the development of AI to the previous technological developments which have impacted the history of athletics is a practice which helps us understand and predict the actions of regulatory bodies in relation to advances which could remove human error in sports on a scope beyond any other tools.

The development of AI processing hardware is key to determining the level of inequity AI would generate in sports. If AI were to become sufficiently economical, concerns about inequities caused by it would be diminished. This would open doors toward the implementation of AI at a larger scale, even at lower levels of athletics.

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Modelling Cancer-Like Stress Responses in *S. cerevisiae* By Isha Agarwal

Abstract

Cancer cells thrive in environments characterized by multiple, overlapping stressors such as oxidative damage, nutrient deprivation, and osmotic imbalance. Understanding how cells adapt to such conditions is essential for studying disease progression and therapeutic resistance. This project conceptualizes *Saccharomyces cerevisiae* (baker's yeast) as a simplified model to investigate multi-stress biology. Yeast cultures were designed to be exposed to five stressors—heat, oxidative stress (hydrogen peroxide), osmotic stress (NaCl), ethanol, and glucose starvation—individually and in selected combinations. Viability was to be assessed through methylene blue staining and culture turbidity, with stress responses compared across conditions. While the experiment remained largely theoretical due to logistical constraints, projected outcomes suggested that combined stressors (e.g., oxidative stress plus ethanol) would synergistically increase cytotoxicity, whereas certain pairings (e.g., heat plus starvation) might reveal partial resilience. These anticipated patterns parallel features of cancer cell stress responses, while also highlighting key divergences, such as the ability of tumor cells to undergo transcriptional reprogramming or enter polyan euploid states. This framework demonstrates how yeast can serve as an accessible model for exploring the limits of cellular adaptation, while emphasizing the broader relevance of stress biology to understanding cancer.

1. Introduction

1.1 Background & Rationale

Cellular stress response systems have evolved to protect organisms against a variety of environmental insults. However, in complex diseases like cancer, these systems are often hijacked, leading to unchecked survival and proliferation under normally lethal conditions. Among the most studied stress types is oxidative stress, but emerging research suggests that cells in vivo rarely encounter a single stressor in isolation.

The study of cellular stress responses is crucial for understanding how cells adapt to adverse environmental conditions. Yeast, particularly *Saccharomyces cerevisiae*, has emerged as a powerful model organism for investigating these mechanisms due to its genetic tractability, conserved eukaryotic pathways, and relevance to both biotechnological applications and human disease (Poștaru et al., 2023) (Taymaz-Nikerel et al., 2016). Tumor microenvironments present a unique set of multi stressors, including oxidative stress, nutrient deprivation, and osmotic changes, which yeast models can effectively mimic and elucidate (Costa et al., 2023) (Ribeiro et al., 2022).

1.2 Significance of Oxidative Stress in Disease (e.g., Cancer)

Oxidative stress, defined as an imbalance between reactive oxygen species (ROS) production and detoxification, is a hallmark of numerous diseases, particularly cancer. It influences mutagenesis, apoptosis resistance, metabolic reprogramming, and drug resistance in

cancer cells. However, oxidative stress is often compounded by other concurrent stressors, such as hypoxia, nutrient deprivation, and acidification, especially within solid tumors. This multi-stress environment enables the selection of aggressive clones that evolve stress-resilient mechanisms, making it critical to investigate how cells adapt under combinations of stress, rather than in artificially isolated conditions.

1.3 Why *Saccharomyces cerevisiae* (Yeast)?

Yeast, particularly *Saccharomyces cerevisiae*, serves as an effective model organism for studying cancer cells due to its genetic and metabolic similarities to human cells. This model allows researchers to explore fundamental biological processes relevant to cancer, including metabolic reprogramming, genomic instability, and the effects of anticancer drugs. The following sections detail the key reasons for yeast's utility in cancer research.

1.3.1 Metabolic Similarities

Yeast exhibits the Warburg effect, where it favors fermentation over oxidative phosphorylation in high glucose conditions, mirroring cancer cell metabolism (Tosato et al., 2013). The regulation of pyruvate kinase in yeast parallels its upregulation in cancer, providing insights into metabolic alterations during tumorigenesis (Tosato et al., 2013).

1.3.2 Genetic Manipulation and Screening

Yeast's rapid generation time and ease of genetic manipulation facilitate high-throughput screening for cancer-related proteins and drug responses (Pereira et al., 2012) (Matuo et al., 2012). The ability to express human oncogenes and tumor suppressors in yeast allows for the study of their functions and interactions in a simplified model (Guaragnella et al., 2014).

1.3.3 Insights into Cancer Mechanisms

Yeast models have been instrumental in understanding the roles of key cancer proteins, such as p53 and BRCA1/2, and their implications in tumorigenesis (Guaragnella et al., 2014). The use of yeast in drug discovery has led to the identification of potential therapeutic targets and the mechanisms of drug resistance (Menacho-Márquez & Murguía, 2007) (Matuo et al., 2012).

1.4 Research Objectives & Questions

This project seeks to investigate the cumulative and combinatorial effects of multiple stressors on *S. cerevisiae* to model complex disease environments.

Our objectives are:

1. To understand stress response pathways interact when *S. cerevisiae* is subjected to more than one stressor.
2. To investigate whether multiple stressors activate synergistic, antagonistic, or novel adaptive mechanisms.

2. Literature Review

2.1 Stress Responses in Yeast

2.1.1. Integrated Stress Response (ISR)

The Integrated Stress Response (ISR) is a conserved pathway that allows cells to respond to diverse stress stimuli by restoring proteostasis. In yeast, the ISR is dynamically regulated, with genetic perturbations influencing its activation and dynamics. For instance, depletion of aminoacyl-tRNA synthetases or tRNA biogenesis factors proportionately activates the ISR, while impaired ribosome biogenesis reduces basal ISR activity (Baum et al., 2024). This highlights the intricate balance between translation capacity and stress response activation.

2.1.2. Hog1 MAPK Pathway

The Hog1 mitogen-activated protein kinase (MAPK) pathway is central to yeast osmoregulation and stress response. Hog1 activation transiently arrests the cell cycle, allowing cells to adapt to stressors like osmotic shock. This pathway also interacts with calcineurin to modulate cell cycle progression and stress adaptation (Leech et al., 2020). Additionally, Hog1 regulates the unfolded protein response (UPR) during ER stress, as evidenced by its role in tunicamycin sensitivity suppression (Hernández-Elvira et al., 2019).

2.1.3. TORC1 Signaling

The target of rapamycin complex 1 (TORC1) is a nutrient-sensing pathway that regulates cell growth and metabolism. Hyperactivation of TORC1 sensitizes yeast to ER stress by compromising cell wall integrity, highlighting the crosstalk between nutrient signaling and stress responses (Ahmed et al., 2019). TORC1 inhibition, however, can enhance stress tolerance by remodeling cellular metabolism.

2.1.4. Yap1 and Oxidative Stress

Yap1 is a master regulator of the oxidative stress response in yeast. Transcriptomic profiling reveals that Yap1 protects yeast from oxidative and other types of stress by upregulating antioxidant pathways and metabolic processes (Zhang et al., 2016). Yap1 mutants are more sensitive to chemicals like tert-butyl hydroperoxide (t-BHP) and methyl methanesulphonate (MMS), underscoring its critical role in stress mitigation.

2.2 Key Stressors in Lab Research

Stressor	Effects on Yeast Cells	Key Pathways and Mechanisms
Oxidative Stress	Induces antioxidant responses, glutathione cycling	Yap1, oxidative stress response pathways (Zhang et al., 2016)

Ethanol Stress	Disrupts membrane integrity, metabolic shifts	Environmental stress response (ESR), Hog1 MAPK pathway (Yang & Tavazoie, 2020)
Osmotic Stress	Activates Hog1 MAPK pathway, cell cycle arrest	Hog1, calcineurin, cell wall remodeling (Leech et al., 2020) (Ribeiro et al., 2022)
ER Stress	Triggers UPR, TORC1 attenuation	Hog1, TORC1, unfolded protein response (UPR) (Ahmed et al., 2019) (Hernández-Elvira et al., 2019)
Nutritional Stress	Reprograms metabolism, ISR activation	ISR, translation regulation, ribosome biogenesis (Baum et al., 2024) (Crawford & Pavitt, 2019)

Table 1 : Key Stressors, Effects, and Pathways in Yeast

2.3 Cell Death and Viability Assays

Cell death and viability assays in yeast, particularly under multistressor conditions, are critical for understanding programmed cell death (PCD) mechanisms and their implications for cellular health. Yeast, especially *Saccharomyces cerevisiae*, serves as a valuable model for studying these processes due to its genetic tractability and conserved pathways with higher eukaryotes. The following sections outline key methodologies and findings related to yeast cell death and viability assays.

2.3.1 Programmed Cell Death (PCD) Assay

Yeast can undergo PCD, exhibiting characteristics similar to mammalian apoptosis, such as chromatin condensation and reactive oxygen species (ROS) accumulation (Côte-Real & Madeo, 2013).

Assays developed for yeast include colony formation and vital dye staining (e.g., FUN1) to quantify cell viability after stress exposure, such as acetic acid treatment (Teng & Hardwick, 2009) (Teng & Hardwick, 2013).

2.3.2 Viability Assessment Techniques

Advanced microscopy techniques, including automated image analysis, allow for real-time monitoring of yeast cell morphology and viability without staining (Tibayrenc et al., 2011).

2.4 Relevance to Human Pathologies

The relevance of yeast-multistressor setups to human pathologies lies in their ability to model complex biological responses and elucidate mechanisms underlying various diseases. Yeast, particularly *Saccharomyces cerevisiae* and *Candida glabrata*, serves as a powerful tool for understanding stress responses that are conserved across species, thereby providing insights into human health and disease.

2.4.1 Yeast as a Model for Stress Responses

Yeast models exhibit a common environmental stress response, revealing gene expression changes that parallel human stress responses (Meena & Chakrabarti, 2015). The study of stress-activated signaling networks in yeast has highlighted similarities with mammalian systems, aiding in the understanding of cancer signaling defects (Ho & Gasch, 2015).

2.4.2 Humanized Yeast for Disease Modeling

Humanized yeast can incorporate human genes, allowing for direct assays of human gene function and the exploration of disease variants (Kachroo et al., 2022).

This approach facilitates high-throughput studies of human biology, enhancing the understanding of genetic contributions to diseases (Kachroo et al., 2022).

2.4.3 Insights into Pathogenic Yeasts

Research on *Candida glabrata* has uncovered mechanisms of drug resistance and stress tolerance, critical for addressing infections in immunocompromised patients (Pais et al., 2019). Understanding these mechanisms can inform the development of new therapeutic strategies against multidrug-resistant infections (Pais et al., 2019).

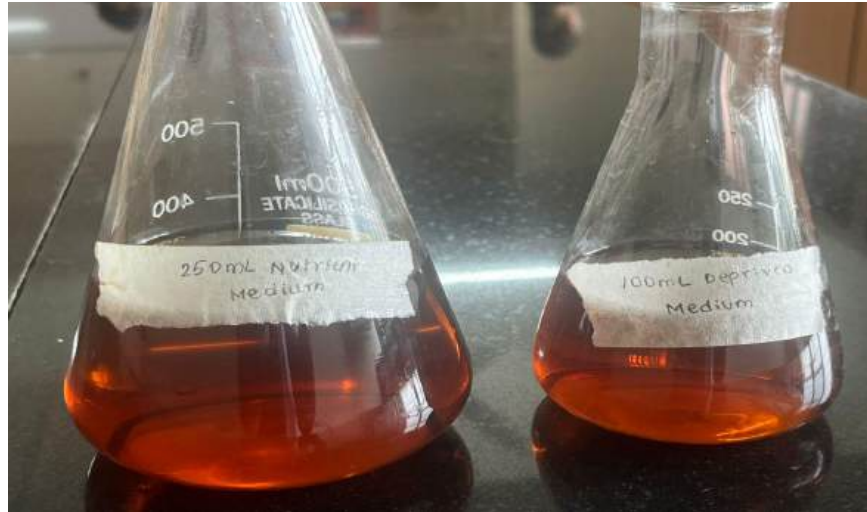
3. Materials and Methods

The following methods outline an idealized experimental protocol conceptualized for the purposes of modeling stress biology in yeast. Due to logistical constraints, the full experiment was not executed.

3.1 Reagents and Materials

Culture Medium

A modified yeast extract peptone dextrose (YPD) medium was prepared using the following components per 250 mL: 5 g sucrose, 5 g peptone, 2.5 g beef extract, and 250 mL warm distilled water.



Yeast Strain

Saccharomyces cerevisiae (commercially available dry baker's yeast) was used throughout the experiment. This strain is non-pathogenic, eukaryotic, and commonly utilized as a model organism in molecular biology.

Stressors Applied

Heat stress: Incubation at 45°C

Oxidative stress: 3% H₂O₂ (500 mM final concentration)

Osmotic stress: NaCl (500 mM)

Ethanol stress: 7.5% v/v ethanol

Nutrient deprivation: Glucose-depleted medium containing 0.02% w/v glucose



Viability Assay Reagents

Diluted methylene blue solution (1:2 dilution with distilled water)

Equipment and General Supplies

Test tubes, test tube racks, sterile cotton plugs, light microscope (40x–100x objectives), droppers or disposable pipettes, glass slides and coverslips, inoculation loop

3.2 Culture Preparation

Yeast Activation and Pre-Culture

Dry *S. cerevisiae* (15 g) was suspended in warm water and incubated for 24 hours to allow for rehydration and initial growth. Foam formation and turbidity were used as indicators of cell activity. Cells were then inoculated into test tubes containing 3 mL modified YPD medium for experimental use.

Culture Medium Preparation

A total of 12.5 g culture medium (as described in 3.1) was suspended in 250 mL distilled water and heated to ensure complete dissolution.

3.3 Stressor Application

Cells were exposed to five stressors individually and in selected combinations. Each stressor was prepared at the working concentrations detailed in *Table 2*.

Stress Type	Agent	Final Concentration
Control	None	Room Temperature
Heat	Hot water bath	45°C
Oxidative	Hydrogen peroxide	500 mM
Osmotic	Sodium chloride (NaCl)	500 mM
Ethanol	Ethanol	7.5% (v/v)

Glucose deprivation	Glucose-limited medium	0.02% (w/v) glucose

Table 2: Applied Stressors and Final Conditions

3.4 Cell Viability Assay

Methylene Blue Staining

After exposure, one drop of culture was mixed with one drop of diluted methylene blue (1:10 with water). A drop of this mixture was placed on a glass slide and covered with a coverslip. Cells were observed under a light microscope. Viable (metabolically active) cells remained colorless, while non-viable cells stained blue.

Visual Assessment

Culture turbidity (scored visually on a scale of 1–5) and foam formation were recorded as additional indicators of growth or cell damage.

3.5 Controls and Replicates

Each condition was tested in triplicate pseudo-replicates. A negative control group without stressor exposure (room temperature, standard YPD) was included.

Condition Type	Description
Negative Control	No stressor, YPD medium
Experimental Groups	Individual and paired stressor exposure
Replicates	3 pseudo-replicates per condition

Table 3: Experimental Conditions

4. Experimental Design

This experimental framework was conceptualized to model stress adaptation in yeast cells and to draw parallels with cancer cell responses. While not fully executed, the design represents a feasible home-lab simulation of conserved stress biology.

4.1 Rationale for Stressor Selection

Each environmental stressor was selected to model conditions relevant to pathophysiological or clinical microenvironments, particularly those observed in cancer biology.

Stressor	Biological Relevance
Heat	Mimics fever or tumor-induced hyperthermia
Oxidative	Models reactive oxygen species (ROS) in tumor environments
Osmotic	Mimics dehydration, high salinity, or chemotherapy-induced stress
Ethanol	Models metabolic and membrane-disruptive stress
Nutrient Deprivation	Simulates energy-starved tumor cores or ischemic conditions

Table 4: Mechanistic Overview of Stressors

4.2 Experimental Workflow

Day 1: Yeast rehydration and pre-culture in modified YPD

Day 2: Stressor application (1-hour exposure) in individual test tubes

Day 2 onward: Post-stress incubation to assess adaptation or recovery

Test Tube Setup

Each stress condition was represented by a set of three tubes:

1. Acute Stress Only – Cells exposed for 1 hour, then incubated post-stress.
2. Sequential Stress Exposure – After initial stress, exposed to a second stressor.
3. Persistent Stress – Remained in stress conditions for 24–48 hours.

Samples were collected and analyzed at 24 and 48 hours post-exposure.

4.3 Sampling and Timepoints

Day	Duration	Activity
Day 1	1 hour	Culture preparation and stressor dilution

Day 2	6 hours	Application of stressors and setup of test groups
Day 3	3 hours	24-hour post-exposure microscopy and turbidity assay
Day 4	3 hours	48-hour post-exposure microscopy and turbidity assay

Table 5: Sampling Protocol

4.4 Safety and Waste Disposal

Although all reagents used are low-risk and household-grade, standard laboratory safety protocols were observed.

PPE: Lab coats, gloves, and goggles were worn throughout.

Ventilation: Hydrogen peroxide and ethanol were handled in ventilated areas.

Biological Waste: All yeast cultures were heat-inactivated prior to disposal.

Chemical Disposal: Diluted chemical waste was flushed with excess water. Methylene blue was collected separately for proper disposal in accordance with local guidelines.

5. Discussion

5.1 Expected Results

Although I did not execute this experiment in full, the projected outcomes based on prior studies and known yeast biology suggest clear patterns in how *S. cerevisiae* would respond to different stressors and their combinations. Under single-stressor conditions such as oxidative stress, ethanol exposure, or heat, I expect a moderate reduction in turbidity and cell viability over 24–48 hours, accompanied by visual changes such as membrane deformation, mild shrinkage, and partial lysis. For instance, oxidative stress is likely to lead to clumping and ROS-induced cell rupture, while ethanol may compromise membrane integrity, resulting in bursting or the appearance of ghost cells under the microscope.

In dual or multi-stressor conditions particularly combinations like oxidative + ethanol or osmotic + oxidative, I anticipate synergistic effects that significantly increase cytotoxicity. These pairings would likely result in over 80% cell death within 24 hours, characterized by low turbidity, minimal foam formation, and reduced or absent budding. Under the most extreme condition; the quintuple combination of ethanol, heat, oxidative stress, osmotic stress, and glucose deprivation I project near-total loss of viability (over 95% by 48 hours), due to overwhelming damage to key stress-response systems. In contrast, yeast exposed to milder dual stresses such as heat + starvation might display partial resilience (approximately 40–60%

viability), potentially due to protective responses such as heat shock protein expression or trehalose accumulation.

These anticipated patterns align with established findings in yeast stress biology and support the hypothesis that cumulative stress can exceed adaptive thresholds. While these results are theoretical, they offer a conceptual framework that could guide future experimental validation and serve as a simplified model for studying stress sensitivity and adaptation, particularly in comparison to cancer cell resistance mechanisms.

5.2 Interpretation of Results (Idealized)

Based on prior studies and current biological understanding, the projected outcomes of the proposed experiment suggest that *Saccharomyces cerevisiae* would exhibit varied growth and viability responses when subjected to different combinations of stressors. Singular stressors such as oxidative stress (H₂O₂) and ethanol are anticipated to reduce cell viability significantly. The hypothetical five-stressor condition comprising ethanol, oxidative, heat, osmotic, and starvation stress is expected to result in the most pronounced growth inhibition due to overwhelming cellular burden.

Some stressor combinations, such as heat + osmotic or oxidative + ethanol, are predicted to exert synergistic effects, where the combined stress impact exceeds the sum of individual effects. In contrast, combinations like starvation + ethanol may exhibit antagonistic interactions, potentially revealing compensatory or adaptive mechanisms, such as metabolic slowing or altered membrane transport.

Based on established yeast stress literature, *S. cerevisiae* may show the greatest hypothetical resilience under the heat + starvation combination. This could be attributed to overlapping protective pathways such as heat shock protein (Hsp) induction and trehalose accumulation. In the full quintuple-stress condition, however, adaptation is unlikely, and near-complete loss of viability (>90%) is expected.

These projected responses reinforce the complexity of stress crosstalk and demonstrate the limitations of stress adaptation when cellular systems are simultaneously challenged at multiple nodes.

5.3 Possible Improvements & Future Extensions

To build on this framework and improve both rigor and resolution, the following extensions are recommended:

Incorporate Molecular Readouts: Techniques such as qPCR or transcriptomics could help identify stress-specific gene expression signatures.

Perform Time-Course Analysis: Measuring viability and morphology at more frequent intervals (e.g., 6, 12, 24, 48 hours) would distinguish between temporary stalling and progressive cell death.

Use a Strain Panel: Including multiple yeast strains (e.g., wild-type, TOR1 mutants, Yap1 knockouts) could help differentiate general vs. pathway-specific responses.

Stress Intensity Gradients: Rather than binary exposure, applying low, medium, and high doses could help define stress thresholds and dose-response curves.

CRISPR or Knockout Screens: In a more advanced lab setting, gene deletion studies could identify essential pathways for stress resilience and synthetic lethality candidates.

Conclusion

This study demonstrates that *Saccharomyces cerevisiae* exhibits pronounced sensitivity to environmental stressors such as oxidative agents, ethanol, heat, osmotic imbalance, and glucose deprivation, especially when these stressors are applied in combination. The decline in viability particularly under dual and quintuple stress conditions, reflects a failure in core cellular maintenance systems, mirroring several characteristics of cancer cell behavior under therapeutic stress. Although this setup reflects a simplified model system, it effectively simulates the types of stress combinations encountered by cancer cells in vivo. The proposed framework supports future investigations into synthetic lethality and stress adaptation using accessible materials. Interestingly, cancer cells, unlike yeast, can develop resistance to such stressors over time, particularly when exposed sequentially. This resistance arises from both genetic and phenotypic adaptations that are context-dependent and often shaped by the tumor microenvironment (TME). For example, certain melanoma cells exhibit stress-resistant gene expression profiles that allow them to survive chemotherapy and hypoxia, forming a rare population of persistent cells (Schaff et al., 2022). In my yeast model, no such persistence was observed under high-stress combination treatments, indicating a lack of inherent adaptation over short timescales.

Moreover, sequential stress exposure in cancer cells has been shown to induce transcriptional reprogramming, which can modify cellular sensitivity to subsequent treatments depending on the order of drug administration (Fasse et al., 2022). In contrast, our experimental yeast model showed additive or synergistic toxicity when stressors were layered, with no evidence of adaptive resilience, highlighting a key divergence between unicellular and transformed multicellular systems. This suggests that while yeast can model acute stress effects effectively, cancer cells possess a broader dynamic range for survival via stress-induced reprogramming.

Another notable divergence lies in the cancer cell's ability to enter a polyan euploid state, a survival strategy in which cells temporarily arrest their cycle to protect genomic integrity and later re-enter proliferation with enhanced resistance potential (Pienta, 2022). Yeast cells, by contrast, underwent irreversible lysis and loss of structural integrity under prolonged stress without evidence of such pausing behavior.

Finally, the role of the TME in promoting multidrug resistance (MDR) through altered metabolism, elevated autophagy, and the emergence of cancer stem cell phenotypes is absent in our simplified yeast system (Seebacher et al., 2021). However, the yeast model remains useful for capturing fundamental stress response mechanisms such as ROS sensitivity, membrane disruption, and nutrient deprivation, which are foundational to understanding cancer therapy response.

While *S. cerevisiae* does not replicate the full complexity of tumor resistance, its responses to layered stress provide a baseline for distinguishing between passive cell death and active adaptation. These findings reinforce the value of yeast as a screening tool for exploring synthetic lethality and stress combinations, while also emphasizing the limitations of such models in capturing the dynamic and plastic resistance mechanisms unique to cancer.

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The Impact of Exercise-Related Metabolites on Metabolic Health By Moran Liu

Abstract

Muscle health and insulin sensitivity are crucial for metabolic homeostasis and overall well-being. This study investigates the distinct effects of succinic acid (SA) and lactic acid (LA), two key metabolites, on insulin sensitivity, myogenesis, and myofiber dynamics. Our results reveal that moderate concentrations of SA enhance insulin sensitivity by increasing the phosphorylation of key signaling proteins such as AKT and ERK. However, higher concentrations of SA promote myofiber degradation, as evidenced by elevated Myostatin levels, indicating a dual role in metabolic regulation and muscle integrity. In contrast, LA moderately enhances insulin sensitivity at higher concentrations without significantly influencing myogenesis or inducing myofiber degradation, suggesting a more protective role in muscle health. These findings have important implications for dietary and metabolic health. Nutritional sources that influence the levels of SA and LA in the body could differentially impact muscle function and metabolic processes. Moderate SA levels may support insulin sensitivity, whereas excessive SA could impair muscle repair and growth. LA, by maintaining muscle integrity, emerges as a safer metabolite in muscle-related interventions. Our study underscores the importance of balanced nutritional strategies in promoting muscle health, particularly through the regulation of metabolite levels. These insights provide a foundation for future research into dietary and metabolic interventions aimed at enhancing muscle integrity, improving insulin sensitivity, and preventing muscle degeneration associated with aging and metabolic disorders.

1. Introduction

1.1 Metabolic Health and Insulin Sensitivity

Metabolic health refers to the body's ability to efficiently regulate and utilize energy, which includes maintaining balanced blood sugar levels, managing cholesterol and triglycerides, regulating blood pressure, and achieving a healthy body weight. Proper metabolic function significantly reduces the risk of chronic conditions such as diabetes, cardiovascular disease, and stroke.

A critical component of metabolic health is insulin sensitivity, which measures how effectively the body's cells respond to insulin, the hormone responsible for regulating blood sugar levels. When muscle, fat, and liver cells are highly sensitive to insulin, they absorb glucose from the bloodstream for immediate use or storage, maintaining stable blood sugar levels. Conversely, insulin resistance, or reduced insulin sensitivity, disrupts this process, leading to elevated blood sugar levels and a heightened risk of metabolic diseases.

Insulin resistance is a major driver of type 2 diabetes (T2D), a chronic condition characterized by persistent hyperglycemia due to impaired insulin action or insufficient insulin production. In the United States, over 84 million adults have prediabetes—a precursor to T2D—emphasizing its widespread prevalence. Insulin resistance disrupts glucose uptake and

often requires increased insulin production, creating a cycle that culminates in prediabetes or T2D. Preventive strategies, including balanced diets, regular exercise, and healthy weight maintenance, are essential for improving insulin sensitivity and supporting overall metabolic health. Factors contributing to T2D include genetics, obesity, certain medications, aging, and sedentary lifestyles, with obesity-induced inflammation playing a particularly significant role in insulin resistance.

1.2 Exercise and Metabolic Health

Regular physical activity is a cornerstone of metabolic health, improving insulin sensitivity, lipid profiles, blood pressure, and body composition. Exercise reduces visceral fat, decreases pro-inflammatory markers, and increases anti-inflammatory cytokines. These effects lower the risk of metabolic syndrome (MetS) and related diseases such as obesity and T2D by enhancing glucose uptake and mitigating systemic inflammation.

Exercise also triggers the production of myokines—cytokines secreted by muscle tissue—and modulates oxidative stress pathways, which are critical for reducing inflammation and preventing metabolic disorders. These physiological adaptations demonstrate the profound link between regular physical activity and improved metabolic health outcomes.

1.3 Exercise-Related Metabolites: Lactic Acid and Succinic Acid

Lactic acid, produced during anaerobic respiration, plays a dual role in muscle function and energy metabolism. During exercise, when oxygen is limited, lactate serves as a vital alternative energy source, linking glycolysis with oxidative phosphorylation and gluconeogenesis. Beyond its role in energy production, lactate influences insulin sensitivity, regulates protein function, and modulates gene transcription, contributing to cell proliferation and epigenetic modifications.

However, excessive lactic acid accumulation can impair muscle function by slowing metabolic processes and increasing inflammation, resulting in fatigue and muscle pain. Although lactate is often associated with muscle fatigue and acidosis, emerging research highlights its function as a valuable metabolic fuel for skeletal muscles, the heart, and the brain. This duality underscores lactate's complex role in energy metabolism and its potential impact on insulin signaling and glucose uptake.

Succinic acid, a key component of the tricarboxylic acid (TCA) cycle, plays an essential role in cellular energy production by supporting ATP generation via oxidative phosphorylation. Recent evidence suggests succinic acid enhances mitochondrial respiration in skeletal muscle, improving oxygen utilization and reducing fatigue. Additionally, succinic acid promotes the transition of muscle fibers from fast-twitch to slow-twitch types, which are more efficient for endurance activities.

While succinic acid shows promise in improving mitochondrial function and reducing muscle fatigue, its role in insulin sensitivity and glucose regulation remains inconclusive.

However, it holds potential as a supplement to enhance muscle energy and function, particularly for individuals unable to engage in regular physical activity.

1.4 Muscle Tissue and Metabolic Health

1.4.1 Muscle Tissue Function and Differentiation

Muscle tissue, composed of specialized fibers capable of contraction, is critical for movement, physical performance, and metabolic health. Skeletal muscle, in particular, plays a key role in insulin-mediated glucose uptake via glucose transporter 4 (GLUT4). A loss of skeletal muscle mass can result in insulin resistance, increased lipolysis, and elevated free fatty acids, which further impair muscle regeneration and exacerbate metabolic dysfunction.

Muscle tissue differentiation is vital for regeneration and function. Factors such as insulin resistance and chronic inflammation disrupt this process, leading to reduced muscle mass and metabolic disorders. Insulin resistance promotes gluconeogenesis and muscle protein breakdown, while chronic inflammation elevates pro-inflammatory cytokines, compounding muscle dysfunction. These disruptions highlight the need for therapeutic strategies aimed at enhancing muscle regeneration and improving metabolic health.

1.4.2 Insulin Sensitivity and Diabetes

Muscle mass and function are closely tied to insulin sensitivity. Sarcopenia, or the loss of muscle mass and strength, is associated with metabolic disorders such as diabetes. Insulin resistance in skeletal muscle impairs glucose uptake, increasing the risk of diabetes.

Myokines, secreted by muscle tissue, are critical for metabolic health. Exercise enhances muscle mass and promotes the release of beneficial myokines such as interleukin-6 (IL-6), which improves glucose uptake, fat oxidation, and insulin sensitivity. Chronic inflammation associated with sarcopenia, however, exacerbates insulin resistance and metabolic dysfunction. Thus, preserving muscle mass and function is essential for preventing insulin resistance and managing metabolic disorders like diabetes.

2. Methods

2.1 Cell culture

C2C12 mouse myoblast cells, obtained from the American Type Culture Collection (ATCC), were cultured in Dulbecco's Modified Eagle Medium (DMEM; Corning) supplemented with 10% fetal bovine serum (FBS; Sigma-Aldrich) and 1% penicillin-streptomycin (Gibco). For myoblast differentiation, the 10% FBS was replaced with 5% horse serum (Gibco). The cells were maintained at 37°C in a humidified atmosphere containing 5% CO₂, and the culture medium was refreshed daily.

To investigate the effects of lactate and succinate on myoblast differentiation, C2C12 cells were seeded in 6-well plates, and treatments with the metabolites began on the third day

following the initiation of differentiation. For studies examining myofiber degradation, the metabolites were introduced seven days after differentiation induction.

To assess insulin resistance, cells were treated with the metabolites, followed by the addition of 100 nM insulin. Samples were collected at various time points, and downstream protein phosphorylation was measured to evaluate insulin signaling activity.

2.2 Western blots

Western blotting was performed to quantify protein levels, following standard protocols. Protein samples were resolved by SDS-PAGE under reducing conditions and then transferred to nitrocellulose membranes (GE Healthcare) using electrophoresis. The membranes were blocked with Odyssey Blocking Buffer (LI-COR) prepared in Tris-Buffered Saline (TBS).

Primary antibodies targeting specific proteins were applied overnight at 4°C, including: Myosin (Sigma-Aldrich, M4276, 1:2000), Myostatin (Proteintech, 19142, 1:2000), Vinculin (Sigma-Aldrich, V9264, 1:5000), Phospho-AKT (S308) (Cell Signaling Technology, 13038, 1:2000), AKT (pan) (Cell Signaling Technology, 4691, 1:2000), Phospho-p44/42 MAPK (Erk1/2) (Thr202/Tyr204) (Cell Signaling Technology, 9101, 1:2000), p44/42 MAPK (Erk1/2) (Cell Signaling Technology, 4696, 1:2000). After primary antibody incubation, membranes were washed three times with TBST and incubated with secondary antibodies—donkey anti-rabbit Alexa Fluor 488 (A-21206; Thermo Fisher Scientific, 1:10,000) or donkey anti-mouse Alexa Fluor 555 (A31570; Thermo Fisher Scientific, 1:10,000)—for 1 hour at room temperature. Fluorescent signals were visualized using the LI-COR Odyssey CLx Imaging System, and data were analyzed for protein quantification.

3. Results

3.1 The Effect of Succinic Acid and Lactic Acid on Insulin Sensitivity

To evaluate the effects of succinic acid (SA) and lactic acid (LA) on insulin sensitivity, C2C12 myoblasts were treated with metabolites at varying concentrations. Insulin (100 nM) was then added to induce signaling, and phosphorylation levels of downstream proteins were measured at 15 and 30 minutes post-treatment.

15-Minute Treatments

Succinic Acid (SA): Phosphorylation levels following SA treatment were comparable to the control group at lower concentrations (SA-1: 100 μ M and SA-2: 200 μ M). As the concentration increased to SA-5 (500 μ M) and SA-10 (1.0 mM), phosphorylation decreased slightly, but at SA-15 (1.5 mM), phosphorylation levels rebounded to match those of the control. This pattern indicates a concentration-dependent modulation, with SA-15 demonstrating the most significant insulin response enhancement.

Lactic Acid (LA): LA treatments showed an overall similar trend but with slightly weaker effects compared to SA. At LA-1 (100 μ M) and LA-2 (200 μ M), phosphorylation was

lower than the control. At LA-5 (500 μ M), phosphorylation increased noticeably, showing a stronger response compared to lower concentrations. This trend continued at LA-10 (1.0 mM), with phosphorylation peaking at LA-15 (1.5 mM). However, LA-15 also exhibited a slight drop in p-ERK, while p-AKT phosphorylation remained elevated.

30-Minute Treatments

Succinic Acid (SA): At 30 minutes, SA treatments consistently enhanced phosphorylation of insulin signaling markers. SA-1 and SA-2 showed moderate increases in p-ERK and p-AKT compared to the control, while SA-10 and SA-15 exhibited the most robust phosphorylation levels, indicating enhanced insulin sensitivity.

Lactic Acid (LA): LA treatments showed less phosphorylation overall compared to SA. While LA-1 and LA-2 demonstrated lower phosphorylation than the control, LA-5 and LA-10 displayed incremental improvements, with LA-15 achieving the strongest insulin response. However, LA-induced phosphorylation remained weaker than SA across all concentrations.

Comparison of SA and LA

Both SA and LA exhibited dose-dependent effects on insulin signaling, with the strongest responses observed at the highest concentrations (SA-15 and LA-15). However, SA consistently outperformed LA, producing stronger and more stable activation of insulin sensitivity markers across both time points. At lower concentrations, SA demonstrated greater phosphorylation enhancement compared to LA, which showed reduced efficacy at these doses.

Overall, the results indicate that SA is more effective than LA in enhancing insulin sensitivity. SA treatments yielded higher phosphorylation levels of key signaling proteins (p-ERK and p-AKT) at nearly all concentrations and time points, highlighting its stronger and more consistent ability to potentiate insulin signaling.

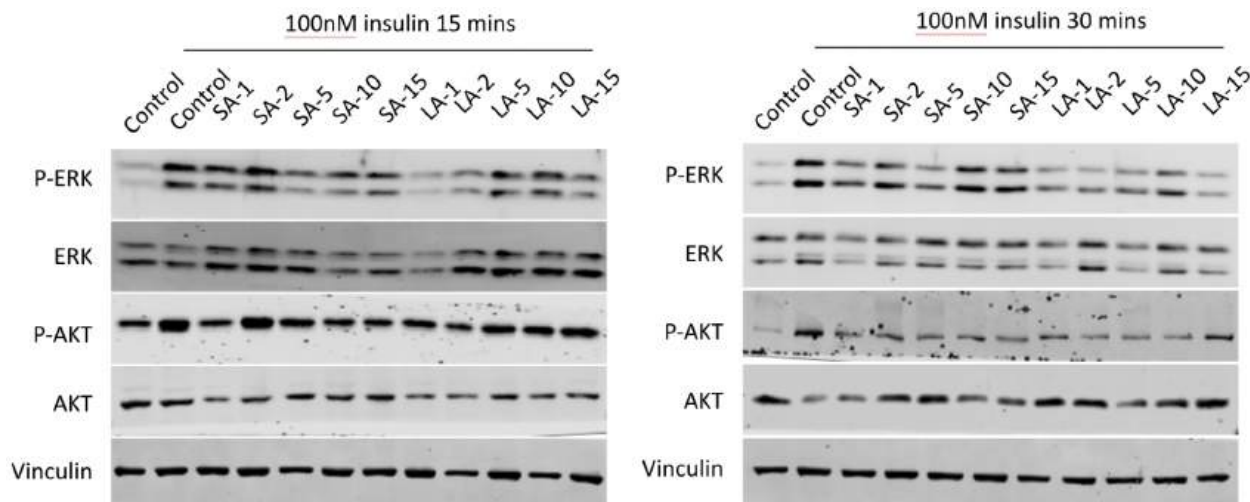


Fig 1: The activity of insulin signaling.

3.2 The Effect of Metabolites on Myogenesis

This study examined the effects of succinic acid (SA) and lactic acid (LA) on myogenesis by measuring the expression levels of Myosin and Vinculin, key markers of muscle cell differentiation.

Succinic Acid (SA): SA treatment significantly enhanced myogenesis in a concentration-dependent manner. At lower concentrations (SA-1 and SA-2), there was a noticeable increase in Myosin and Vinculin expression compared to the control, indicating a stimulatory effect on muscle cell differentiation. The expression of Myosin peaked at SA-5, suggesting that this concentration was optimal for promoting myogenesis. However, at higher concentrations (SA-10 and SA-15), the expression of Myosin and Vinculin declined, indicating that excessive amounts of SA might inhibit the differentiation process after reaching its peak efficacy at SA-5.

Lactic Acid (LA): In contrast, LA treatment did not produce significant changes in Myosin or Vinculin expression at any concentration. The levels of these markers remained comparable to the control group, suggesting that LA has no substantial impact on myogenesis or muscle fiber differentiation.

These findings demonstrate that succinic acid plays a significant role in promoting myogenesis, the process by which myoblasts differentiate into myotubes, contributing to muscle fiber growth and repair. The highest expression of Myosin and Vinculin was observed at SA-5, indicating that a moderate concentration of SA is most effective in supporting the differentiation of myoblasts into myotubes and facilitating muscle regeneration.

Interestingly, higher concentrations of SA (SA-10 and SA-15) resulted in reduced expression of differentiation markers, suggesting a dose-dependent biphasic effect. While moderate levels of SA promote muscle cell differentiation, excessive concentrations may exert inhibitory effects, potentially due to metabolic stress or feedback inhibition mechanisms. This underscores the importance of maintaining an optimal concentration of SA for efficient muscle fiber development.

In contrast, LA did not influence myogenesis under the conditions tested, indicating it is not a significant modulator of muscle cell differentiation or growth. The results highlight succinic acid as a potent enhancer of myogenesis at moderate concentrations, supporting its role in muscle fiber formation and regeneration. Conversely, lactic acid does not appear to contribute to muscle cell differentiation in this model. These findings suggest a potential application of succinic acid in therapies aimed at improving muscle regeneration and repair, provided that its concentration is carefully regulated.

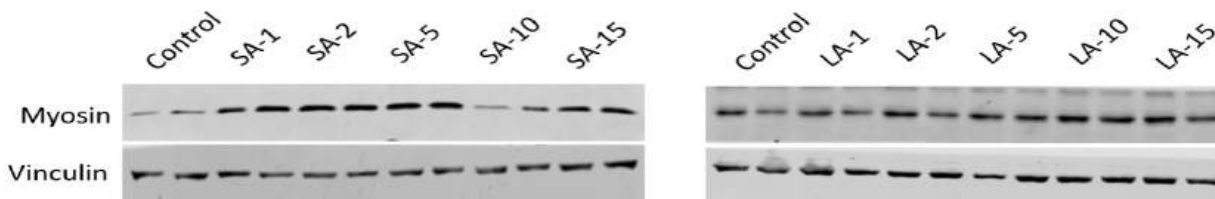


Fig 2: The effect of succinate and lactate treatment on myogenesis.

3.3 The Effect of Metabolites on Myofiber Degradation

This study investigated the effects of succinic acid (SA) and lactic acid (LA) on myofiber degradation, as indicated by the expression levels of Myostatin, a key regulator of muscle breakdown.

Succinic Acid (SA): The data suggest that SA promotes myofiber degradation in a concentration-dependent manner. In the Control group, Myostatin expression was minimal, reflecting normal myofiber formation with negligible degradation. At low concentrations (SA-1 and SA-2), there was a slight increase in Myostatin levels compared to the control, indicating the early onset of myofiber degradation. At SA-5, Myostatin expression reached a noticeable peak, suggesting significant promotion of muscle fiber breakdown. This effect became even more pronounced at higher concentrations (SA-10 and SA-15), where Myostatin levels were at their highest. The consistent increase in Myostatin expression with rising SA concentrations suggests a dose-dependent enhancement of myofiber degradation, potentially interfering with muscle regeneration and growth.

Lactic Acid (LA): In contrast, LA treatment showed no significant effect on Myostatin levels. Across all tested concentrations (LA-1, LA-2, LA-5, and LA-10), Myostatin expression remained similar to the control group, indicating that LA does not influence myofiber degradation under the experimental conditions.

These results demonstrate that succinic acid promotes myofiber degradation in a concentration-dependent manner, with high concentrations (SA-10 and SA-15) strongly enhancing Myostatin expression. While low levels of SA (e.g., SA-1 and SA-2) may not substantially hinder muscle regrowth, higher concentrations appear to exacerbate muscle fiber breakdown, potentially impairing muscle repair and growth. This suggests that excessive exposure to SA could be detrimental to muscle health, particularly in contexts requiring robust muscle regeneration.

Conversely, the lack of significant changes in Myostatin expression with lactic acid treatment implies that LA does not contribute to myofiber degradation. This suggests that LA is less likely to interfere with muscle repair and regeneration processes compared to SA. The findings highlight a stark contrast between succinic acid and lactic acid in their effects on myofiber degradation. While SA promotes the breakdown of muscle fibers at higher concentrations, potentially limiting muscle regeneration, LA does not appear to impact this process. These results suggest that succinic acid must be carefully regulated in contexts involving muscle repair or growth to avoid adverse effects, while lactic acid may be neutral in such scenarios.

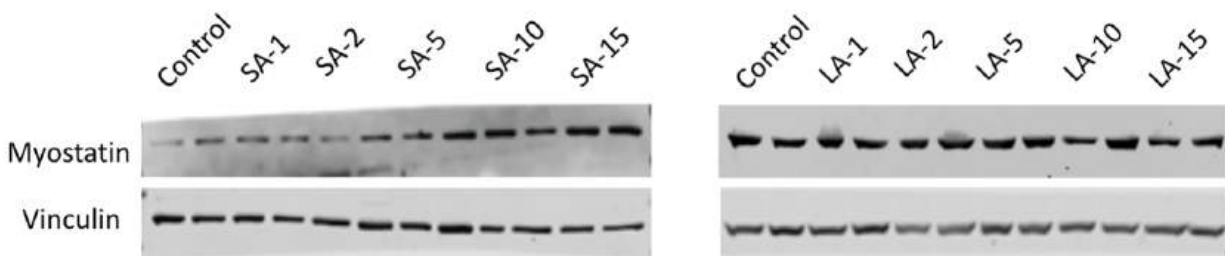


Fig 3: The effect of succinate and lactate on myofiber degradation.

Discussion

Our findings reveal distinct roles for succinic acid (SA) and lactic acid (LA) in regulating myofiber dynamics and insulin sensitivity, with significant implications for muscle health and potential applications in nutrition and daily life.

Succinic acid displayed dual roles in muscle physiology. On one hand, moderate concentrations of SA enhance insulin sensitivity, as demonstrated by increased phosphorylation of key signaling proteins such as AKT and ERK, which are critical mediators of glucose uptake and metabolic regulation. On the other hand, higher concentrations of SA promoted myofiber degradation by upregulating Myostatin expression, a known inhibitor of muscle growth and repair. This suggests that while SA may support metabolic health at certain levels, excessive accumulation could compromise muscle integrity and function.

In contrast, lactic acid had a more modest effect on insulin sensitivity, with enhancements primarily observed at higher concentrations. Notably, LA did not significantly influence Myostatin levels, suggesting it does not contribute to myofiber degradation. This indicates that LA may have a protective or neutral role in maintaining muscle integrity, even under conditions of metabolic fluctuation. Together, these results highlight the nuanced and context-dependent roles of these metabolites in muscle health.

Succinate and lactate are intermediates in cellular metabolism, and their levels can be influenced by dietary intake and metabolic state. Foods rich in succinate precursors, such as certain fermented products and citric acid cycle intermediates, may increase succinate levels in the body. Similarly, lactate levels can be elevated through the consumption of carbohydrate-rich meals, especially under conditions of intense physical activity or anaerobic metabolism.

These findings underscore the importance of dietary patterns in modulating muscle health. A balanced diet that avoids excessive accumulation of succinate or lactate precursors may help optimize muscle function. For example, moderation in the intake of highly processed foods that may elevate succinate levels could help prevent potential myofiber degradation. Conversely, incorporating nutrient-dense carbohydrates to support lactate production during exercise may enhance metabolic function without compromising muscle integrity.

Muscle health is a critical determinant of overall well-being, particularly as it relates to mobility, metabolic regulation, and resistance to age-related decline. These findings suggest that targeted nutritional interventions could play a pivotal role in maintaining muscle integrity and function. For instance, moderate consumption of succinate-rich foods could be explored as a

strategy to enhance insulin sensitivity, potentially benefiting individuals with metabolic disorders such as diabetes. However, caution is warranted regarding excessive succinate accumulation, which may impair muscle repair and growth.

Lactic acid, on the other hand, presents a safer profile in terms of muscle health, as it does not promote myofiber degradation. Encouraging activities or diets that favor lactate production, such as aerobic and anaerobic exercise combined with appropriate nutritional support, could help sustain muscle function and metabolic health.

Muscle health is essential for maintaining physical independence, preventing chronic diseases, and improving quality of life. Nutritional interventions that balance the levels of metabolites such as succinate and lactate could serve as practical strategies to promote muscle health. This is particularly important as sedentary lifestyles and poor dietary habits become increasingly prevalent. Tailoring dietary recommendations to support optimal metabolite levels while mitigating potential adverse effects can provide a foundation for enhancing muscle function and preventing age-related muscle degeneration.

By elucidating the distinct roles of succinic acid and lactic acid in muscle dynamics and insulin sensitivity, this study highlights the intricate interplay between metabolism, diet, and muscle health. These findings not only enhance our understanding of muscle physiology but also emphasize the potential for nutritional interventions to support muscle integrity and metabolic function in daily life. Further research into the dietary regulation of these metabolites and their broader impacts on muscle and metabolic health will help pave the way for evidence-based nutritional strategies aimed at improving human health.

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Electric Vehicle Tensions
An Event Study of Chinese EV Corporations and Western Trade Protectionism
By Stephen Lazuardi

Abstract

This paper examines how Western policies impact global electric vehicle (EV) markets, with a focus on Chinese manufacturers. Using a classical event-study approach and Fama-French five-factor models, we analyze daily stock price reactions to Western policy announcements and Chinese EV product launches. Results show that Chinese product launches tend to negatively impact global competitors, highlighting their growing market power. In response, Western trade policies cause immediate, statistically significant losses for Chinese EV firms, though they have limited positive effects on Western companies. The findings suggest that while protectionist policies can weaken foreign rivals, relieving competitive pressure, they do not necessarily lead to appreciable gains in expected profits for domestic incumbents.

Introduction

The ascent of China's electric vehicle (EV) industry has rapidly reshaped global supply chains and triggered growing concern among Western policymakers. In response, a wave of trade restrictions, tariffs, and industrial policies have emerged, aimed at curbing China's growing competitive edge in the sector. These policies, framed as efforts to protect western domestic industries, have had ripple effects on global financial markets, especially on Chinese EV firms. This paper examines the impact of Western policy actions on Chinese EV stocks by employing an event study methodology that estimates a counterfactual model for stock prices and measures the effects of the above described events as the difference between actual stock returns and predicted returns under the counterfactual model, had the events not occurred. The counterfactual model used is the 5-factor Fama and French (2015) model, a workhorse model in empirical asset pricing to describe the cross-section of stock returns. I study a range of announcements such as tariffs, export controls, and government industrial strategies on stocks and I find that Western trade policies have a statistically significant, immediate negative effect on Chinese EV corporations. The impact on Western manufacturers is more muted, with generally low positive abnormal returns recorded. In parallel, new product launches by Chinese firms lead to both economically and statistically significant negative effects on Western car manufacturers' stocks.

The existing literature highlights the continuous evolution of policy measures aimed at promoting and regulating the EV sector. Peng, Liangui, and Li (2022), for example, provide a comprehensive timeline of China's new energy vehicle (NEV) policies from 2004 to 2020. Their analysis introduced a new "Policy Intensity" (PI) index designed to gauge the impact of distinct policy measures over time. The study categorized policies into three phases: (i) promotional/technological measures from 2004 to 2008, (ii) financial policies between 2009

and 2013, and (iii) charging infrastructure from 2014 to 2020. The study not only illustrates a clear evolution but also demonstrates that promotional policies exerted the greatest influence.

Similarly, Belton, Graham, and Xia (2020) examine the broader industrial strategy of China. Their research investigates the “Made in China 2025” initiative, the foundation of China’s policy to upgrade its manufacturing sector. Concentrating on early research and development (R&D) initiatives and city-level subsidy programs, the authors contend that early interventions such as the 863 Program were pivotal in stimulating Chinese technological breakthroughs, particularly in lithium-ion battery technologies and electric drive systems. They argue that such proactive measures facilitated the country’s technological progress and that US trade policies, which largely relied on tariffs and unilateral sanctions, were fundamentally reactive and insufficient to counter China’s strategic investments. The study proposes four possible methods of countering Chinese growth: develop new trade remedy tools, employ non-trade policies, engage with allied nations, and develop a national competitive plan to boost U.S. R&D support, with the most promising path being a national competitive plan.

Hinh T. Dinh (2024) further analyzed the policy shifts under the Biden administration, which have introduced higher tariffs on a range of Chinese imports including EVs. Drawing on U.S. import statistics and official government statements, his study explains that although the volume of affected imports is relatively small in the short term, such policies signal a significant strategic shift. These moves are intended to protect U.S. domestic labor and manufacturing capabilities while setting the stage for broader economic decoupling from China. As a result, even symbolic policy announcements can alter market perceptions, therefore substantially affecting investor sentiment and stock performance.

Further insight is provided by studies that employ quantitative methods to trace the direct impacts of trade policy on EV outcomes. Kouam (2024), for instance, adopts a mixed-methods framework that merges quantitative analysis through multiple linear regression with qualitative expert interviews. The regression model incorporates variables such as tariff levels, supply chain disruptions, and domestic market share, while controlling for external factors like GDP and technological capacity. Results from this analysis indicate that higher tariffs and supply chain disruptions significantly erode EV production and sales, whereas a rising domestic market share tends to bolster market performance. Complementing these findings, Saussay (2024) employs a two-step modeling approach to simulate the effects of Trump’s proposed tariff measures on both the European and global economies. Utilizing detailed product-level data and input-output models, Saussay’s study argues that although broad tariff proposals might yield only temporary protection for domestic industries, their long-term impacts can be severe for China, whose exports could be forced into alternative markets. Together, these quantitative studies underscore the direct, negative ramifications that trade policy shocks can have on EV market outcomes; since financial markets are forward-looking, such effects can be directly estimated by analyzing the response of abnormal stock returns as done in this paper.

On top of tariff-focused studies, past studies have also modelled global supply chain dynamics. Busch et al. (2024) developed an integrated model for international electric vehicle

trade that forecasted future EV demand and battery production requirements using simulations based on historical light duty vehicle data and battery characteristics. Their analysis revealed that the future of global EV trade may be characterized by regional production blocks; North America might continue to depend heavily on imports even as China shifts towards meeting its domestic demand. This regional realignment suggests that increases in EV demand do not necessarily translate into proportional local production boosts, a disconnect that can have profound implications for stock market valuations in the sector. Similarly, Bown (2024) investigation into EU economic security probes the complex interplay between Chinese industrial strategies, US-imposed tariffs, and the ensuing redirection of Chinese exports toward the EU. This study provides evidence that traditional policy instruments such as tariffs yield only short-term market adjustments while leaving long-term supply chain shifts largely unaddressed.

Finally, some literature explores the effectiveness of various domestic policies intended to stimulate plug-in electric vehicle (PEV) adoption. Zhou, Levin, and Plotkin (2016) conduct a literature review which synthesized findings from 18 studies conducted primarily in the U.S.; it highlights that a combination of financial and non-financial incentives can substantially boost PEV adoption rates. Their review shows that tax credits, subsidies, HOV lane access, and adequate charging infrastructure all contribute to increased EV uptake. Importantly, the review notes that while large direct vehicle incentives may have limited impact in the absence of sufficient charging infrastructure, well-calibrated policies yield the best results. Although this work is centered on domestic U.S. policy before 2016, its insights are broadly applicable worldwide. It reinforces the idea that the effectiveness and subsequent market impact of policy announcements is contingent upon the comprehensive design of the incentives and infrastructure investments that underpin them.

Overall, past literature has emphasized both positive and negative impacts of policy announcements. Historical assessments and policy evolution models underscore that high-intensity, proactive policy measures such as those adopted during China's early NEV promotion phase can provide momentum and confidence that favorably influence market performance. Conversely, quantitative studies reveal that abrupt tariff announcements and trade restrictions tend to disrupt market operations, diminish production capacities, and create geopolitical tensions that weigh on investor sentiment. Moreover, simulation models suggest that these policy measures also shape long-term structural shifts in global supply chains, resulting in regional market realignments.

This paper approaches EV research through a quantitative analysis of high-frequency financial market responses to policy announcements. According to the efficient market hypothesis, financial markets immediately price in new information; therefore, such policy events can have a near-instantaneous effect on the stock performance of Chinese EV firms. The literature reviewed above utilized quarterly or annual data that focused on the long-run effect of policy strategies. However, by relying on higher frequency stock returns data, this paper can cleanly isolate the effects of such policies from other events and thus drastically reduce the possibility that confounding factors may be driving the results. As such, this study can provide

policymakers with insights into the effects of protectionist policies as perceived by financial markets.

Data

1. Financial Market Data

This study uses daily close data (adjusted for dividends and stock splits) from Yahoo Finance, focusing on major car manufacturers across the United States, Europe, and Asia. Table 1 introduces the companies observed in each region along with identifying information. To construct the 5-factor counterfactual model, we download factor data from Kenneth French’ personal website.

Table 1. Companies Observed in Each Region with Identifier

Company	Ticker	Region	Exchange
Tesla Inc.	TSLA	United States	NASDAQ
General Motors Co.	GM	United States	NYSE
Ford Motor Co.	F	United States	NYSE
Fisker Inc.	FSR	United States	NYSE
Rivian Automotive Inc.	RIVN	United States	NASDAQ
Lucid Group Inc.	LCID	United States	NASDAQ
BYD Company LTD.	1211	China	HKEX
Geely Automobile Holdings Ltd.	175	China	HKEX
SAIC Motor Corporation Ltd.	600104	China	SSE
Contemporary Amperex Technology Co. Ltd. (CATL)	300750	China	SZSE
NIO Inc. (ADR)	NIO, 9866	China	NYSE, HKEX
Li Auto Inc. (ADR)	LI	China	NASDAQ
XPeng Inc. (ADR)	XPEV	China	NYSE
Mercedes-Benz Group AG	MBG	Germany	FWB
Bayerische Motoren Werke AG (BMW)	BMW	Germany	FWB
Volkswagen AG	VOW3	Germany	FWB
Renault SA	RNO	France	EPA

2. Event Observation Data

For policy events, we hand-crafted a dataset of twenty-seven product launch announcements from a variety of sources—mainly news articles, automobile shows, and company websites. The two main categories of events analyzed are trade/industrial policy announcements by Western governments and product launches by Chinese EV manufacturers. Wherever possible, we tried to identify the earliest date at which a given policy became known to public markets, even if that date precedes the one of the official policy announcement; this is important to control for possible anticipation effects since financial markets are forward-looking and rumours or discussions surrounding official policy announcements often circulate prior to the official announcement. To assemble the policy dataset, we conducted a manual web search, scanning government portals (WhiteHouse.gov, Europa.eu, etc.) and major news services

(Reuters, Bloomberg, Time, etc.) for announcements that explicitly referenced electric-vehicle rules or trade measures. Table 2 shows policy announcement date, event name, event type, source, and the positively or negatively expected company ticker. A similar table for product launches can be found in the Appendix. In Table 2, there are 2 types of policies: (i) domestic incentives: tax credits, subsidies, etc. and (ii) trade barriers/protectionist policies, including tariff-based and non-tariff measures.

Table 2: Table of Policy Announcement Date, Name, Type, Description

Date	Policy Name	Type	Description
8/16/22	US Inflation Reduction Act	Domestic Incentive	Expanded subsidies for domestically manufactured EV's
9/20/23	France excludes Chinese EV's from eligibility criteria	Trade Restriction	Disqualified Chinese-made EV's from subsidies or registrations
10/3/23	EU anti-subsidy investigation against china EV's	Trade Restriction	Formal inquiry into whether Chinese EV firms receive unfair government support
5/3/24	US EV tax credit regulations	Domestic Incentive	Clarified rules that negatively impacted vehicles using Chinese components
5/14/24	US quadruples tariff on Chinese EV	Tariff	Increased import duties on China-manufactured EV's
6/13/24	EU increases tariffs on Chinese EV's	Tariff	Broader European tariff response targeting China's perceived state-supported EV industry
11/5/24	Trump Wins US Elections	Anticipated Trade Restriction	Election results signal a desire for stricter protectionist trade policies
3/26/25	Proclamation 10908	Tariff	Imposed a 25 % national-security tariff on imported passenger vehicles and key auto parts, aiming to rebuild domestic supply chains and reduce reliance on foreign components.
4/2/25	Liberation Day	Tariff	Introduced a 10% baseline reciprocal tariff on all imports along with higher country-specific rates and a flat 25% duty on all car imports.
5/12/25	Executive Order 14298 Reduces Reciprocal tariffs on Chinese goods	Tariff	Temporarily reduced the Liberation-Day tariff schedule after U.S. talks; replaced China-specific duties with a flat 10% surcharge for 90 days on all Chinese imports, including EVs and parts.

Regarding motivation, domestic subsidies and other incentives allow policymakers to stimulate local manufacturing capacity and lower the effective cost of manufacturing a domestic EV. In doing so, governments hope to push consumers and firms toward domestic supply chains. On the other hand, trade barriers and tariffs are used to hobble foreign competitors; these are generally justified on the grounds that foreign rivals benefit from unfair subsidies or state

support, or that foreign rivals operate under more benign labor or environmental laws and thus face lower costs than domestic manufacturers.

Methodology

The econometric framework used throughout this study follows the classical event study, e.g. see Campbell, Lo, and MacKinlay (1997). For every firm i at time t , we compute abnormal returns $AR_{i,t}$ as the difference between actual and predicted returns under the counterfactual model:

$$AR_{i,t} = R_{i,t} - \hat{R}_{i,t}$$

where $R_{i,t}$ is the stock's realized logarithmic return and $\hat{R}_{i,t}$ is the logarithmic return predicted by the counterfactual multifactor model. We estimate the counterfactual model using one year of data ending one month prior to the event to ensure that the counterfactual is not contaminated by any anticipatory effects.

Specifically, we estimate the following regression for each firm i separately:

$$R_{i,t} - r_t^f = \alpha_i + \beta_i X_t^c + \mu_{i,t}$$

where α_i is the intercept and β_i captures the exposure of stock i to the $K \times 1$ vector of region-specific risk factors X_t^c . We use different factors depending on the region of the main listing of the stock: US, Europe, and Asia ex-Japan.

For the risk factors, we used the 5-factors of Fama and French (2015): market excess return (Rm-Rf), size (SMB), value (HML), profitability (RMW), and investment (CMA). Individual abnormal returns tend to be noisy; therefore, to assess the effects of the policies given above, we conduct statistical inference on the average abnormal returns and cumulative average abnormal returns, as is standard in the literature. These are calculated over the event window, which we define as starting five trading days (one week) prior to the event and lasting up to twenty-one trading days (one month) afterwards. Starting the event window prior to the event allows us to capture any residual anticipatory effects which we may not have controlled for properly when dating the policy events.

$$CAAR_{[0,h]} = \sum_{k=0}^h AAR_{t+k} \qquad AAR_t = \frac{1}{N} \sum_{i=1}^N AR_{i,t}$$

The test statistic we use to assess the statistical significance of the (cumulative) average abnormal returns is the non-parametric GRANK-T test by Kolari and Pynnonen (2011). The test statistic correctly controls for event-induced variance increase, which may lead one to misattribute the effects of policies to changes in mean instead of changes in variances; it also controls for cross-sectional correlation in abnormal returns which may occur if multiple firms are impacted by the same event and likely to respond in similar fashions (as would be expected for the policies listed above).

Results

Table 3 presents results for all events analyzed jointly: policy announcements and product launches. Inspecting the CAAR's shows that the impact of policy events or product launches lead to immediate negative abnormal stock returns of 1.11%, falling to -2.2% at longer horizons and stabilising afterwards. However, since all events and companies are included in that analysis, this mixes stocks which should benefit from some policies (e.g., Western car manufacturers should record positive abnormal returns following a tariff announcement targeted at their foreign competitors) with other stocks which should be negatively impacted such announcements (e.g., Chinese EV manufacturers should register negative abnormal returns following a tariff announcement targeted at them).

Overall though, the table shows for the sample of events we record, losses inflicted on competitors, either through Western firms facing competition from new Chinese EV models or Chinese firms facing tariffs by Western governments, overwhelm offsetting gains, and the aggregate reaction is decisively negative and statistically significant at the 99% level at most horizons.

Table 3. Table of Cumulative Average Abnormal Return (CAAR_All) for the impact of policy events or product launches on both Chinese and Western companies

Horizon	Number of Events	CAAR	GRANK-T p-val.
[-5;-1]	421	-0.98	0.00***
[-5;0]	421	-1.29	0.00***
[-5;5]	421	-1.11	0.02**
[-5;10]	421	-1.17	0.23
[-5;20]	408	-2.2	0.00***

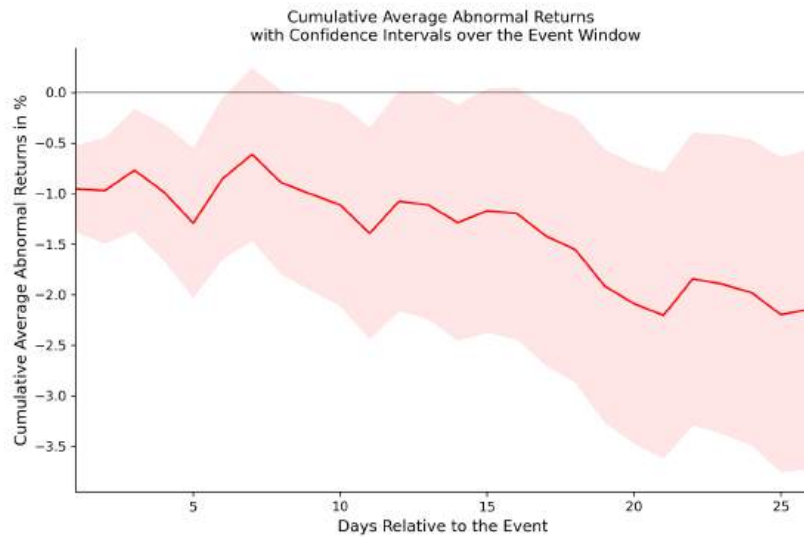


Figure 1. Graph of Cumulative Average Abnormal Return (CAAR_All) for the impact of policy events or product launches on both Chinese and Western companies

In Figure 1, we also provide a visual depiction of the CAAR's. It should be noted that the uncertainty bands displayed in those charts are the usual t-statistics confidence intervals. The latter are not robust to event-induced variance changes or cross-sectional correlation in abnormal returns, but they are the only bands which can be computed for abnormal returns and provide a sense of the uncertainty surrounding the estimates, though it is clear from the results given in Table 1 that the GRANK-T test is substantially more accurate. Similar comments apply to Figures 2, 3, and 4 given below.

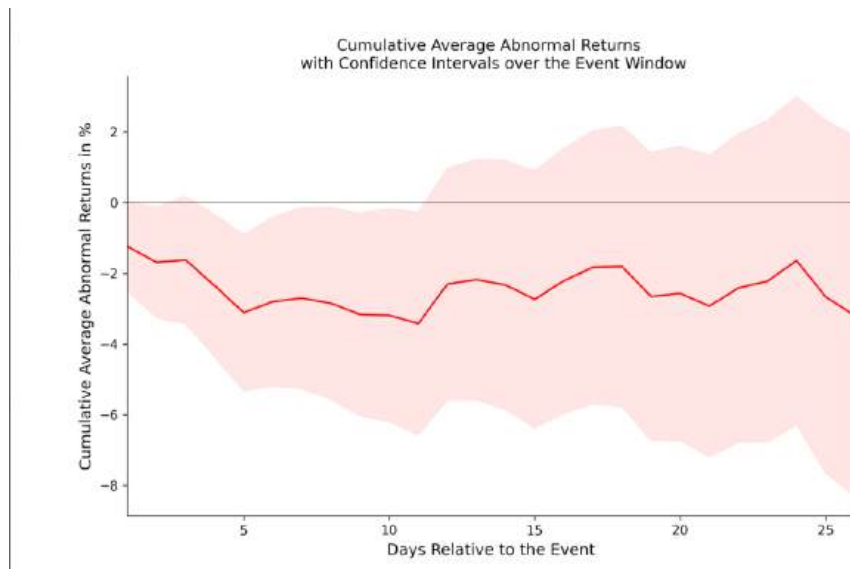


Figure 2: Graphs of CAAR for Western Trade Policy Impact on Chinese EV Corporation

Economically, these results indicate that policy announcements and product launches can have large effects on stock valuations. To give a sense of the magnitude of these estimates, consider that the average market capitalization of the studied Chinese companies is \$59.5 billion dollars. A 2.2% drop thus translates into an average loss of \$1.3 billion loss in equity. Furthermore, for EV giants like Tesla, single-digit decreases in their valuation can lead to tens of billions of dollars in losses. For established Chinese companies such as BYD and CATL, which both have market capitalizations of over \$130 billion, these damages could add up to a \$3billion decrease in value. Not only do such drops negatively affect short-term investor confidence, but they may also hinder long-term R&D investment, expansion initiatives, and supply-chain stability.

We now turn to analysing the effects of Western policy announcements separately on Chinese and Western car manufacturers, with results given in Table 4 and 5 and Figures 2 and 3 below.

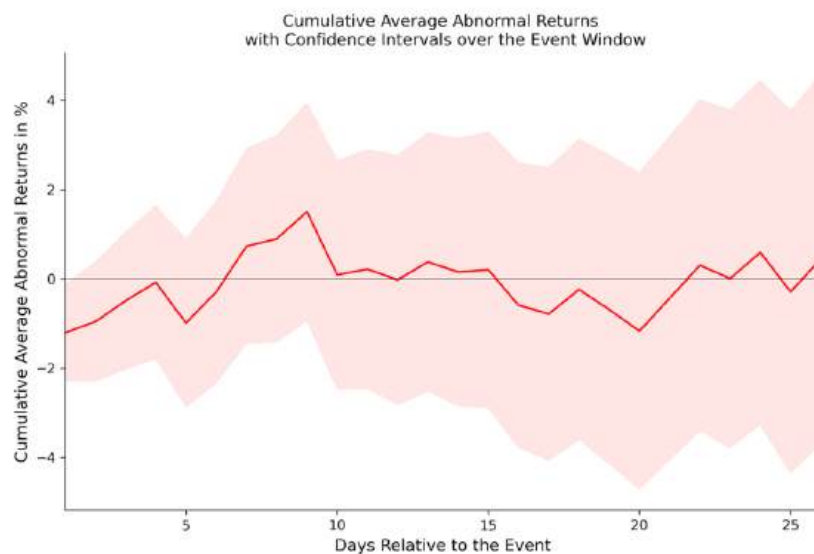


Figure 3: Graph of CAAR for Western Trade Policy Impact on Western EV Corporation

Table 4: Table of CAAR for Western Trade Policy Impact on Chinese EV Corporation

Horizon	Number of Events	CAAR	GRANK-T p-val.
[-5;-1]	66	-2.35	0.00***
[-5;0]	66	-3.11	0.00***
[-5;5]	66	-3.18	0.00***
[-5;10]	66	-2.73	0.02**
[-5;20]	58	-2.66	0.18

Broadly speaking, the effects of such policies are mixed. Chinese EV stocks react negatively to such announcements, with abnormal returns sliding from -2.35% pre-announcement to below 3% throughout the first week following. On the other hand, Western EV stocks remain mostly flat, oscillating around 0 for the 20 trading days following the policy announcement.

Specifically, Table 4 shows that Chinese EV stock registered a CAAR of -3.11% in the [-5,5] event window. However, it is important to note that there are strong anticipatory effects. In the five trading days prior to day 0, we register negative abnormal returns of 2.35%. These pre-event declines are statistically significant (GRANK-T $p < 0.01$), pointing to systematic information leaks and rumours preceding official policy announcements. This could occur because of extensive informal policy signaling, whereby policymakers often discuss or pre-empt major policy announcements. Similarly, news outlets may divulge information regarding new policies prior to these being announced. An example of a clearly anticipated policy could be Biden’s quadrupling of tariffs on Chinese EV’s on May 14, 2024. While the date recorded was the first official record of the announcement, On May 9th 2024—three trading days before the official proclamation—Reuters reported, citing officials familiar with the deliberations, that the White House would unveil the measure the following Tuesday. These leaks were immediately picked up by financial terminals and major news-wires, and while they didn’t cite specific amplitudes of tariffs, they gave investors a notable head-start, possibly explaining the -2.35 % average abnormal return observed in the [-5;-1] window.

Table 5: CAAR for Western Trade Policy Impact on Western EV Corporation

Horizon	Number of Events	CAAR	GRANK-T p-val.
[-5;-1]	62	-0.08	0.00***
[-5;0]	62	-0.99	0.00***
[-5;5]	62	0.09	0.63
[-5;10]	62	0.2	0.96
[-5;20]	57	-0.29	0.00***

For western companies, there is little to no significant pre-announcement drift (CAAR: -0.08%), most likely due to the overall muted effect of policy events on Western markets. Again, we note the high persistence of the estimated effects and the drift towards larger values (in absolute terms) as the event horizon increases. Such phenomena have been reported in other event studies on stock returns, most notably for firm earnings surprises. The Post-Earnings Announcement Drift (PEAD) phenomenon, whereby stock returns continue to follow the direction of an earnings surprise for weeks after the initial announcement due to investor under-reaction/uncertainty (see e.g. Bernard & Thomas, 1989) has been extensively documented. Although our event study focuses on policy announcements rather than earnings announcements, we document similar effects. This trend can most clearly be seen in Table 3, where the CAAR begins at -0.98% in anticipation, but slowly increases in magnitude to -2.2% by the 20th trading

day. However, in terms of whether Western policy events negatively affect Chinese EV manufacturers, the drift effect is much more suppressed. In Table 4, the CAAR for the $[-5; 0]$ event window is significantly negative, starting at -2.35% before climbing to -3.18% by the 5th trading day. On our longest horizon $[-5; 20]$ the CAAR settled to -2.66%, a smaller shift than the $[-5; 5]$ horizon, but still larger than the initial anticipation.

Table 6: Table of CAAR_ALL for Impact of Product Launches

Horizon	Number of Events	CAAR	GRANK-T p-val.
$[-5;-1]$	283	-0.89	0.00***
$[-5;0]$	283	-1.05	0.00***
$[-5;5]$	283	-1.12	0.00***
$[-5;10]$	283	-1.26	0.34
$[-5;20]$	283	-2.78	0.00***

Table 5 indicates that Western trade policies produce little to no statistically significant abnormal returns for Western EV corporations, possibly due to the anticipation of retaliatory policies from China, as observed from the tit-for-tat strategies seen in both of Trump's terms in office. For instance, in July 2018, after the U.S. imposed Section 301 tariffs on Chinese goods, China retaliated by reinstating a 25% tariff on U.S.-made automobiles and auto parts. This directly impacted American EV and auto manufacturers like Tesla, which was forced to raise its Model S and X prices in China by up to \$20,000, weakening its competitive position in the world's largest EV market. Such retaliatory actions signal to investors that even protectionist policies intended to help domestic firms may provoke countermeasures that offset or reverse potential benefits, thus potentially explaining the muted or negative market reaction among Western EV stocks.

Another possible reason for the muted response may be gleaned from behavioral finance: investors are generally risk-averse, i.e. they react more strongly to adverse events compared to positive ones. As a result, negative policy shocks may trigger sharper repricing in Chinese markets than the equivalent positive response in Western stocks. Still, Western tariffs appear to fulfill their primary objective in eroding Chinese EV stock valuations, i.e. expected discounted future profits. Across the 66 observations in our sample, such policies caused Chinese manufacturers to experience a statistically significant -3.11% CAAR in the $[-5;0]$ window and continued to experience a 2% decrease in CAAR twenty trading days later (Table 4). Although Western tariff policies may fail to increase expected profits for domestic car producers, they consistently succeed in undermining the market valuations of Chinese EV companies, and thus may achieve their primary objective of shielding domestic firms from foreign competition. Nonetheless, it is important to note that the stock returns response will not capture potential consumer welfare losses due to higher EV prices for foreign cars and as such only provide a partial description of the economic effects of such policies.

Table 7: Table of CAAR for Effect of Chinese Product launches on Western Companies

Horizon	Number of Events	CAAR	GRANK-T p-val.
[-5;-1]	138	-0.85	0.00***
[-5;0]	138	-0.98	0.00***
[-5;5]	138	-0.95	0.00***
[-5;10]	138	-0.69	0.78
[-5;20]	138	-2.45	0.00***

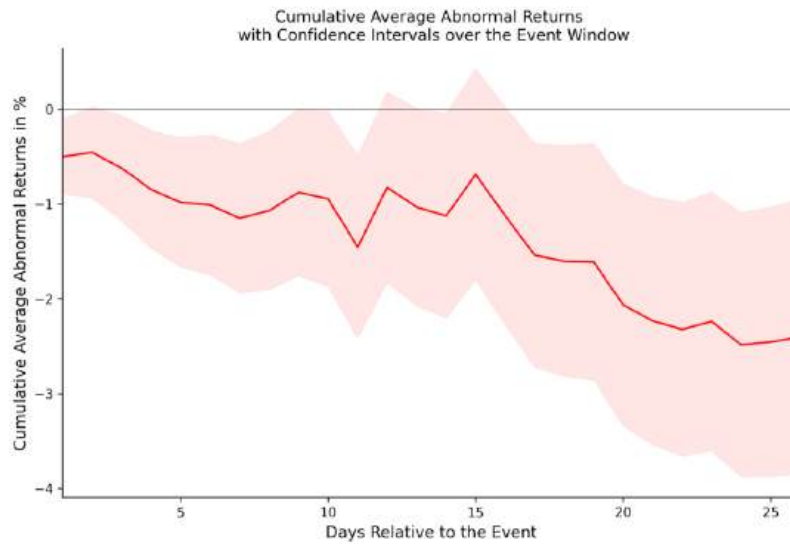
**Figure 4:** Graph of CAAR_ALL for Impact of Product Launches

Table 6 emphasizes the effect of Chinese product launches on financial markets. In reaction to product launches by Chinese EV manufacturers, Western EV stocks register negative abnormal returns dipping from -0.89% in the five-day anticipation window to -2.78% by day 20. Intuitively, it is reasonable that every other manufacturer other than the firm producing the new model would experience losses due to increased competitive pressure. Notably, the speed at which Chinese EV car producers made technological breakthroughs (revealed in such product launches) may have also startled financial market participants.

Our final figure serves to confirm the relevance of our research question. A parallel trend clearly emerges from comparing Figure 4 and Figure 5; Western car companies experience large losses in stock valuations following Chinese EV product launches, while Chinese car manufacturers are in turn negatively impacted by protectionist Western trade policies.

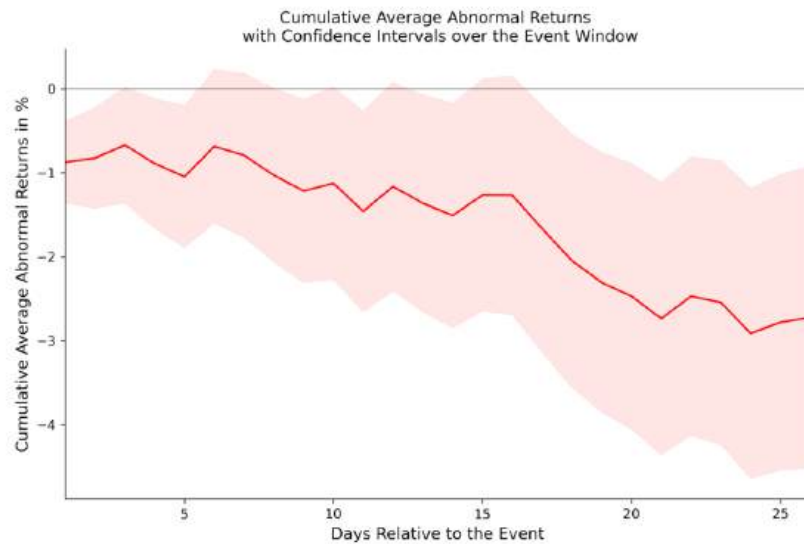


Figure 5: Graph of CAAR for Effect of Chinese Product launches on Western Companies

Conclusion

This study aimed to explore a single question: *How do Western policy actions move both the Chinese and Western EV markets?* Using a classical event study framework on daily stock-price data for 17 leading EV manufacturers, we estimated the cumulative average abnormal returns with a counterfactual model constructed from the Fama-French five factors. The most important findings are as follows: (i) protectionist Western policies aimed at China (tariffs, export controls, investigations) produce an immediate and statistically significant hit to Chinese EV valuations, $\sim -3\%$ in the $[-5; 0]$ window, while Western firms only register muted responses which are by and large neither statistically nor economically significant; (ii) markets price in a large share of the effect prior to the official announcement, indicating either information leakage or clear policy signaling; (iii) the estimated effects are highly persistent and reminiscent of the PEAD.

Future research could explore the responses of specific sectors to such policies (e.g., battery production, autonomous systems, or raw materials). Furthermore, the apparent pre-announcement impact could be deeper studied by integrating Natural Language Processing (NLP) models. Finally, future work should explore policy effectiveness in the long term, not just through short-run market reactions. A multi-year panel analysis could evaluate how trade barriers influence firm fundamentals such as revenue growth, R&D spending, supply chain reconfiguration, and international expansion.

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How Minstrelsy Shaped Race Relations in 1800s America By Beatrice Kim

Abstract: Minstrelsy's Impact on Early American Identity

In the early 1800s, music shaped the course of history. At a time when the culture of America's common man had not yet been firmly established, a question of urgent import given renewed conflict with Britain, minstrelsy emerged. As I show through an analysis of primary sources, minstrelsy offered a black and white vision of the world. Its primarily Irish performers created lasting stereotypes about Black Americans at a time when their own status was in flux, cementing the Irish's own place within America's racial hierarchy and dissolving national differences amongst White European immigrants. The impact of minstrelsy on race relations over time can be seen in the Jim Crow laws of the late 1800s and continues to impact America to this day.

Introduction

In 1828, Thomas Dartmouth Rice, a white New Yorker, stepped onstage in Louisville with his face covered in black ash, and proceeded to sing, joke, and tease the audience, poking fun at African American workers and plantation slaves (Pilgrim and Library of Congress). By 1832, Rice was performing nightly across New York (World History Edu). Indeed, the shows were an immediate and enormous success, even reaching popularity in England (Scriven). Almost twenty years later, in 1852, shows were "listened to by crowds of delighted people," with positive reviews and advertisements for performances becoming a regular feature in the New York Times (The New York Times 1). By 1891, even for amateur minstrel performers on their second performance, like the New York Athletic Club members at Music Hall, "the audience filled every box and every seat in the big house" (The New York Times 8).

The new performance genre emerged at an inflection point in America's cultural history. Renewed conflict with the British, continued debate over abolition, and increasing immigration from Ireland, had driven to the fore questions of American cultural identity. In response to this cultural insecurity, minstrelsy offered a black and white vision of the world. Its primarily Irish performers created lasting stereotypes about Black Americans at a time when their own status was in flux, cementing the Irish's own place within America's racial hierarchy and dissolving national differences amongst European immigrants. The impact of minstrelsy on race relations is directly referenced by the Jim Crow laws of the late 1800s, named after Rice's most famous character. Yet, the belated repeal of these laws and the rewriting of minstrel songs like "Oh! Susanna" have not been able to effectively erase the racial antagonism which minstrelsy nourished. To understand contemporary America, we have to understand how minstrelsy defined race in America.

An 'American' Culture?

As the newly established country settled into its independence after the War of 1812 renewed conflict with the British, America struggled to define its society and culture. As a

country of immigrants, America had a patchwork of different national and religious communities rather than a single cohesive culture. Military opposition to the British became a driving factor for the American desire to reject the British values which had originally defined the early colonies' culture (Toll).

While wealthy Americans wanted to bring European forms and concepts to new heights of achievement, middle and working class Americans wanted instead to be able to shape the country in their own image. They wanted a "common man's culture" that glorified American democracy and the average White man over European aristocracy and the image of a refined "gentleman" (Toll).

To emphasize this, Toll draws a contrast between two types of characters present in 19th century American literature that reflect common American ideals (Toll 7). James Fenimore Cooper, for instance, created Natty Bumppo, a chivalrous gentleman with manners unchanged by the rough outdoors (Toll 7). He spoke with eloquence and rejected payment for his good deeds (Toll 8). Better suited for the parlor than Wild America, the character celebrates British and European ideas of the noble gentleman, yet in the transposition seeks to demonstrate the superiority of Americans in fully realizing these values (Toll 8). By contrast, another character emerged, appealing to the common man, who was brash, defiant, and rude, conquering and building cities out of the untamed, dangerous wilderness (Toll 7). Davy Crockett is the best example of this. He fights for pure joy, wrestling with nature and winning (Toll 8). This was the complete antithesis of what the upper class wanted to embody as Americans. This image of American grit reinforced European claims that Americans were uncouth, to much of the American gentry's chagrin.

Toll suggests that while both images persisted, it was the common man's version that cemented itself as truly American (Toll 8). He argues that minstrelsy and the stage was one of the few places where, despite the rowdy characters upon which it relied, initially little fragmentation took place. While audiences were separated by class, with socialites reserving seats in elevated boxes, while noisy viewers filled the gallery and pit, they enjoyed the same performances. It was a sign of how compelling minstrelsy was, despite its celebration of a common man's version of America. "Davy Crockett would have been perfectly at home there. People got in fights, others competed with the performers, and still others somehow snored through it all [...] Whenever they enjoyed a speech, song, or bit of acting, they cheered and demanded encores" (Toll 10). While these audiences would later split, as symbolized by the Astor Place Riot of 1849, its explicit exile of the British performers is interpreted by Toll as confirmation of the popular form's place in American culture (Toll 16).

Toll's vision of America's search for its own cultural identity finds resonance in the arguments of Gutman and Roediger (Gutman). They argue that the need for a cultural transformation and/or identity was also a function of shifting labor relations. 1815 to 1919 were defined not merely by American expansion but also industrialization (Gutman). Work, especially factory work, became a larger part of the common American's life, through rigid work schedules encouraged by increasingly mechanized workplaces. The Protestant influence on American

society also emphasized restrained behavior, with excessive enjoyment of drinking or leisure time seen as sinful impulses that distracted from work and were to be repressed. Because of the lack of labor laws and general knowledge of health and medical science, there was a high risk of death in the workplace. Deaths were frequently caused by exhaustion and unsafe workplace machinery operation. These factories and workshops were the equivalent of a modern-day sweatshop (Roediger).

By 1919, when this industrial culture had been firmly established, it was normal for the first English lessons for immigrants to begin with terms describing the American working culture and emphasizing maximizing work efficiency and the strict workplace schedules (Gutman). As industry grew, supported by the development of new forms of machinery over the course of the early-19th century, rather than agricultural pioneers, new immigrants and Americans increasingly became employees and workers in workshop settings (Lee).

This shift required a similar shift on the part of Americans, new and old, who were in no way habituated to this. This is particularly visible in the case of Irish, who only migrated in significant numbers to America in the early- and mid-19th century. The need to create a unified culture from disparate groups of immigrants and the sharp shift in norms demanded by steady industrialization created a space for minstrelsy, which condemned laziness and revelry, while leaving space for audiences to indulge, and offered moral superiority to disciplined workers, through its racist characterizations of African Americans.

The Irish Question

The Irish in particular had a difficult time assimilating in America. America already hosted well-established communities of German, British, and Dutch immigrants. Despite the importance of the English and colonial connections to Britain, these communities were well integrated. Like the British, the Dutch and Germans were predominantly protestant. They were admired for their hard work, had established communities throughout the Northeast, and had supported independence. It had even been a German newspaper which had first published the Declaration of Independence (in translation) (Library of Congress). Yet the Irish were different. Relatively few had arrived in America prior to the 18th century. Colonial subjects, and predominantly catholic rather than protestant, their position in the hierarchy was unclear.

Colonized by the British in the 12th century, the Irish were poorly regarded. They were often likened to wild animals, prone to having excessive numbers of children, violent, and resistant to education, as can be seen in Jonathan Swift's 1729, "A Modest Proposal". Intending to mock these stereotypes and inspire reflection on the part of the British, Swift suggests that the Irish could sell their children as food. These stereotypes could exist because of the harsh reality that the Irish faced as tenant farmers, living on small plots paying high rents to absentee British landlords. Furthermore, as Catholics, many faced discrimination from the Protestant government.

Overpopulation, successive crop failures, and a near total absence of industrial opportunities in Ireland, led desperate Irish people to immigrate to America over the course of the 19th century. The most famous of these waves came because of the potato blight. Between

1845 and 1852, a fungal-like organism called *Phytophthora infestans* terrorized Ireland's potatoes. Given the population's overreliance on the potato and the successive crop failures this brought, this caused widespread famine. The British did little or nothing, with over 1 million people dying, and a similar number emigrating.

Those who emigrated boarded disease-ridden crammed ships nicknamed "coffin ships" due to the overwhelming numbers of deaths onboard (Library of Congress). These ships had few, if any, sanitary facilities, berths sufficient for perhaps as little as a sixth of the passengers, insufficient provisions, and high instances of disease (National Museum of Ireland). These miserable conditions were often exacerbated by unnecessary delays, like the eight extra weeks taken by *Elizabeth and Sarah* (Library of Congress). On this ship, 42 of the 276 passengers died. Ireland's population plummeted and eventually New York had more Irish people than Dublin (Library of Congress). Almost half of all migrants were Irish in the 1840s (National Museum of Ireland). The emigration was named the 'American wake' and was considered to be something akin to exile (National Museum of Ireland).

However, this was certainly not the last of their problems. Most—if not all—only had enough money for the ship fare and once they arrived, were homeless and had to reside by the docks or in alleyways (National Museum of Ireland). They were blamed for spreading illness and for their abysmal living conditions which often lacked clean water and sewage disposal, both of which were outside of their control (Library of Congress).

As they looked to find jobs, signs reading "No Irish Need Apply" popped up everywhere from newspapers to windows (Klein). Desperate for money, women "became servants or domestic workers" while men performed hazardous physical labor including railroad construction. This reached a point where deaths were so common that it could be half joked, half acknowledged that "[there was] an Irishman buried under every tie" (Library of Congress). The Irish were deemed easily replaceable and were readily employed in heavy industry.

This exposure to danger did not save them from further discrimination. Their willingness to work for low wages drew consternation and anger from other parts of American society. Still, this mobilization against the Irish often took place through the lens of religious discrimination. The Know-Nothing Party, perhaps the US' first anti-immigrant party, existed in the 1850s almost entirely to oppose the influx of Irish Catholics into the United States, even fomenting violent mobs (Boissoneault). The Irish were also constant targets of the Ku Klux Klan. The Ku Klux Klan at the time consisted of Anglo-Saxon Protestants who were not only anti-black, but anti-immigrant and anti-Catholic, a hatred which persisted into the mid-20th century (History).

Ultimately, compared to the Germans and British settlers, the Irish were new arrivals to America and their position in the hierarchy was uncertain. Historically, they had been subordinate to white British people. The racial hierarchy established Irish people as the lowest rung in White society (Roediger). As a result, Irish people in America were stereotyped to be disease-ridden, unskilled, and were isolated because of the prominence of Catholicism among Irish people (Klein).

Over the course of the 19th century this began to change. As Toll puts it, "until the great

impact of Harriet Beecher Stowe's novel *Uncle Tom's Cabin* after 1851, blacks were only minor characters in drama and literature (Toll 28). In American drama, N****es assumed the comic relief role that the ignorant Irish servant played in England, supplemented by some images of happy slaves." The status of the Irish had risen in society, by virtue of the deterioration of that of African Americans. This was a function of minstrelsy, whose performers, though not exclusively Irish, took up and developed an Irish tradition.

The Aesthetics of the Minstrel Show

American blackface minstrelsy, while a distinctly 19th century invention, drew on a long tradition of oral music and storytelling, especially from Irish and later other folk cultures. Irish immigrants brought elements of this minstrel heritage to America, traveling across the States to perform songs and skits in groups or as individuals. These minstrels were typically working class and had only limited formal education (Toll). Their performances served not only as entertainment but as news, as they traveled across the country they picked up and reported news from place to place (Lee). These shows eventually drew in an expanded audience, as minstrel entertainers rapidly grew in popularity (Toll).

In 1830, when the first blackface minstrel character was invented, race became the primary subject of these shows (Holloway). Through grotesque African American caricatures which offered blackness as a shared target of mockery, minstrelsy would go on to create common ground for the emergence of whiteness, creating a total boundary between the two (Roediger).

Minstrels would "black up," or paint themselves in blackface for skits. These skits mocked African Americans' body features and their traditions, depicting them as immature and impulsive. Haverly's *Complete Guide to N**** Minstrelsy* describes how "blacking up" is done. Actors would slather on cocoa butter, then apply a mixture of cork ashes and water to their skin. In order to make their lips appear larger, they were instructed to apply the paste half an inch or more away from the mouth (Haverly). In shows, blackface minstrels would even joke that they digested ink to prevent their skin from turning pale (Toll 67).

The mask was just one element of this grotesque transformation, which sought to alter their bodies through costume and make-up to generate exaggerated, stereotyped versions of the purported physical characteristics of black people, including large lips and feet, or bulging eyes. Their sheer alienness suggested the complete otherness of black people, and were used to emphasize the idea that Black people were inferior to White people (Lee). Some blackface minstrels even wore animal materials to replace human characteristics (Toll 67). They would use sheep wool as a substitute for hair and would call their children d***y cubs (Toll 67). These choices were deliberate and carried through to the rest of their portrayal. The characters enjoyed an animalistic lifestyle that consisted of consuming possums and raccoons while spending their free time singing and dancing (Toll 67).

Minstrel costumes also continued this bizarre, exaggerated theme. Men wore ridiculous and comical wigs as accessories to gaudy clothes. They wore "knee trousers made of black cloth or satin, a swallow tail coat of red or some bright color with a vest to match; white or colored

shirt with large wing collars, patent leather, low-cut shoes, and black stockings” (Haverly). There was a deliberate contrast between the blackface performers and the ‘whiteface’ performers, who wore formal dress outfits, that made the rest of the company’s outfits seem tacky (Britannica).

Performing a Minstrel Show

The structure of the minstrel show is often credited to Christy’s Minstrels, a group fronted by the ballad singer Edwin Pierce Christy and founded in Buffalo, NY in 1843. By 1855, their format had become widely used. It consisted of two acts, the “walkaround”, and the “olio”, with the possibility of a short play as a third act. The performers were divided into end men, who wore blackface, and interlocutors, who wore whiteface (Britannica). There were typically only one or two interlocutors.

The interlocutor, also known as a middle man, stood in the center surrounded by end men positioned in a semicircle around him (Britannica). At one end of the semicircle was positioned a performer with a tambourine, with another performer holding a bone clapper instrument facing him (Britannica). These were primarily for comic effect, as the instruments that accompanied the acts were the banjo and violin (Britannica).

The production would begin with the “walkaround”. The company waltzed in and positioned itself in a semicircle, while singing a vocal chorus. At the end, the interlocutor would announce that everyone should be seated (Britannica). The performance formally began with a series of songs spanning multiple genres, including ballads, interspersed by jokes and skits (Britannica). A performance by Christy’s Minstrels in 1849 included hits such as “Dinah’s Wedding Day, from the Opera of Losers”, “Rosa Lee, or don’t be foolish Joe”, and “Phantom Chorus, or the D*Turkey’s apparitions, from La Sonnambula”. The jokes were simple and often relied upon the end man failing to understand something. As in the following case:

“Bones: I love to sit by the fire on a winter’s night and tell funny tales.

Mid: You mean anecdotes.

Bones: I mean tales.

Mid: Anecdotes is the better word.

Bones: Is it the better word?

Mid: Yes.

Bones: I have a new dog, a spitspoodle. I have changed his breed to that of a fox terrier.

Mid: And how?

Bones: I cut off his anecdote” (Courtright 64).

On other occasions, they aimed at interaction with the crowd, teasing audience members. “Mr. (name someone in the audience) went into a restaurant the other day and when the waiter gave him a bill of fare [a menu], said: “Thank you, I never read before meals” (Haverly 20).

Nor are the jokes always about racist mockery. There is, as I will discuss later, an element of jealousy at the freedom that African Americans are imagined to enjoy, and which minstrels

and urban workers are in the process of losing. In the following joke, the end man cuckolds the interlocutor.

“End Man: That girl of yours is a sweet kisser.

Mid: How do you know?

End Man: Oh, I had it right from her own lips” (Haverly 15).

Each part of performances were often given a comical name specific to the particular troupe, including Grand Carnival D’Ethiope or Voyage Musical (Haverly). The “olio”, or second act, was a series of individual performances typically longer than the introductory first act, that included dances, speeches, or a more detailed reenactment of a specific scene. Many of these performers were significant attractions on their own and were individually named on playbills. A third act was not always performed, but in the case of the 1849 performance by Christy’s Minstrels was devoted to an extended skit about African American plantation workers.

Language

End men were required to be able to sing and use “good ne*** dialect” (Haverly). The dialect they used was more than a simplified version of English, instead relying upon misspellings or phonetic alterations, incorrect grammar, and caricatured speech patterns. By using this dialect, minstrels reinforced the racist notion that Black Americans were inherently uneducated or unintelligent. In reality, enslaved people were often legally prohibited from receiving formal education and those who attempted to pursue education in secret faced severe punishment (Dehmani). The use of this dialect in performance did not just parody speech—it mocked black people by suggesting they were incapable of mastering standard language or expressing themselves in complex ways. This was part of a systematic infantilization of African Americans, with minstrels depicting them as childlike, unable to resist their urges, and unable to exert themselves continuously at any one task (like studying). Lee cites J. H. Woods’ song “Close Dem Windows” as an example of this, noting that the characters immediately stop working (“close dem windows”), and give themselves over to baking and partying, as they dance and sing that they’ll “have a hap-py time on the inside. Dar’s/ we will make dat fid-dle ring” (Lee).

The contrast between the end men and the interlocutor was there to further add to the ridicule as they maintained “a great deal of dignity and also [spoke] in a clear distinct voice so that the entire audience [heard] his repeating or reply of every line spoken by end men” (Haverly). To achieve this effect, the interlocutor had to “refrain from laughter, if possible” (Haverly). Clearly, their lines were meant to be funny and serve as entertainment for the audience.

The irony of this was that audience members were liable to have only had a limited education and to speak English in a heavily accented fashion. Indeed, there were significant regional variations not only in pronunciation and vocabulary, but even grammar. In a sense then,

by hearing right and wrong pronunciations, the immigrants were able to learn and practice proper English at Black people's expense.

Characters in the Minstrel Show: Zip Coon

Popularized by George Washington Dixon's song "Zip Coon", the eponymous character was hardly novel. His origins traced back to "Raccoon", an elderly libertine played by a black performer in a 1767 musical, the first to be published in America, which came to be called Yankee Doodle (Roediger 49). Despite this history, the word "coon" was far more frequently applied to white Americans prior to 1848, specifically "a white country person [...] a sharpster or, in phrases like a pretty slick coon, to both" (Roediger 50).

Roediger argues that the first clear use of "coon" as a racial slur came only in 1848, linking its use to the blackface minstrel character, "Zip Coon" or "Urban Coon" (Roediger 50). The characters associated with this term were given to indulgence, and portrayed as foolish, irresponsible, and unable to control themselves.

"Zip Coon" could easily be pointed out amongst other onstage performers as he wore flashy and gaudy clothing. He wore the usual swallow-tail coat that minstrels wore, but paired with striped pants, a top hat, and wide lapels (Lemons). The character strutted across stage with failed elegance and acted haughtily (Lemons).

While some have argued that the word is dehumanizing, as the word itself is derived from the raccoon, this history, as Roediger argues, suggests that it is better understood as an index of the transformation of American (and new American immigrants) ideas of a good life, away from entertainment and towards protestant restraint (Roediger 5).

Most importantly, Zip Coon was known for his pretensions. He spoke and acted as if he were knowledgeable, a "mighty learned scholar (Rosenberg). Yet his logic was skewed and his speech was marred by grammatical errors (Lemons). This reinforced White people's beliefs that they naturally held intellectual superiority over Black people. "Zip Coon" would spend his time strutting, styling, and making a fool out of himself (Pilgrim). This caricature depicted what White people thought of free African Americans.

Such racist characters and slurs were reassuring to White people who were insecure about their status in the social hierarchy (Roediger). Increasingly in the postbellum period, the word "coon" took on a life of its own, coming to stand for general laziness, irresponsibility, and work shirking. Pilgrim writes that, "coon" came to mean "unreliable, crazy, lazy, subhuman creatures good for nothing more than eating watermelons, stealing chickens, shooting crap, or butchering the English language" (Pilgrim).

Minstrels' Music

The traditional American folk song "Oh! Susanna" is widely taught and performed today, often perceived as a harmless, nostalgic tune. However, its origins trace back to the mid-19th century and are deeply entangled with the racist traditions of minstrel performance. The song was originally composed by Stephen Foster, a prominent American songwriter, in 1847. Despite

Foster's authorship, the song was subsequently pirated and republished under the name E. P. Christy, founder of Christy's Minstrels (Finn and Foster).

"Oh! Susanna" was among the first minstrel songs to "enter the middle-class market," signaling a shift in how minstrel material was viewed by mainstream audiences (Finn and Foster). While the lyrics of "Oh! Susanna" have since undergone substantial revision leaving no overtly offensive language in modern adaptations, this sanitization obscures the song's original context and deeply troubling content:

"Oh! Susanna" by Stephen Foster

I came from Alabama, Wid a banjo on my knee,
I'm gwyne to Louisiana, My true love for to see.
It rain'd all night the day I left, The weather it was dry,
The sun so hot I froze to death; Susanna, don't you cry.

Chorus:

Oh! Susanna, Oh don't you cry for me,
cos' I've come from Alabama, Wid my banjo on my knee
I jumped aboard the telegraph, And trabbled down the riber,
De lectric fluid magnified, And killed five hundred n*****.
De bullgine bust, de horse run off, I really thought I'd die;
I shut my eyes to hold my breath, Susanna don't you cry.

CHO: Oh Susanna &c.

I had a dream the odder night, When ebery thing was still
I thought I saw Susanna A Coming down de hill;
The buck-wheat cake was in her mouth, The tear was in her eye;
Says I, "I'm coming from de south, Susanna, don't you cry."

CHO: Oh Susanna &c.

I soon will be in New Orleans, And den I'll look all round,
And When I find Susanna, I will fall upon de ground.
And If I do not find her, Dis D*****'l surely die,
And when I'm dead and buried, Susanna, don't you cry.

CHO: Oh Susanna &c. (Ditson)

The original lyrics of "Oh! Susanna" contains disturbing and violent imagery, including a casual reference to the mass murder of five hundred African Americans, presented in a comedic tone. Given that minstrel shows were designed to entertain predominantly white audiences, this line was likely intended as a dark "joke"—one deeply unsettling from a contemporary perspective.

The song also features improbable and nonsensical imagery. For instance, the protagonist supposedly travels on an electrical telegraph down a river, a scenario which defies physical logic

and highlights the character's supposed ignorance. This implausibility likely serves a dual purpose: to evoke humor and to reinforce the minstrel trope of the dull-witted, buffoonish Black character. In keeping with minstrel conventions, the language of the song is deliberately simplified and written in a stereotyped African American dialect. Words such as "dis" (this), "riber" (river), and "odder" (other) are used not for dialectal accuracy but to mock and dehumanize.

Moreover, the song can be interpreted as mocking interracial attraction. The Black protagonist's affection for Susanna—a character perhaps modeled after Foster's own sister, Charlotte Susanna Foster, who died at the age of nineteen—is portrayed as unrequited and inappropriate. It is plausible that the fictional Susanna was white, given her historical namesake. The line referring to "buckwheat cake in her mouth," which readers have speculated was a marriage custom in the South, may symbolize her marriage to another man, reinforcing the theme of racial and romantic exclusion. Regardless of the true original interpretation, it is clear that the protagonist does not and cannot realize his love.

Although the modern rendition of "Oh! Susanna" omits racial slurs, the original version included several, reflecting the deeply racist attitudes embedded in 19th-century minstrel culture. The song appears heavily inspired by Silas Steele's 1846 composition "Rose of Alabama", which was published two years earlier and shares notable similarities in melody (both are written in the key of G), dialect, and narrative structure. Both songs feature a journey down a river, use simplified dialectal English, reference electricity "lightnin'" and include an accident. However, while "Rose of Alabama" maintains some of the mocking tone characteristic of minstrelsy, it is comparatively less overt in its racial hostility. The characters in Steele's song may be portrayed as clumsy or foolish, but the affection between them is not questioned, and Rose herself is described as beautiful and desirable without irony or ridicule. Their love is realised. This contrast underscores a critical point: Stephen Foster made a deliberate choice to include explicitly racist language and imagery in "Oh! Susanna," intensifying the dehumanization present in earlier minstrel works he drew upon. His adaptation thus reflects a conscious escalation in racial stereotyping, rather than mere imitation.

Minstrelsy goes National!

Minstrelsy continued to gain popularity throughout the 1840s, with performing troupes traveling across the entire country and even reaching Europe. Just fifteen years after the first blackface minstrel show, the Ethiopian Serenaders marked the overwhelming popularity of minstrelsy by performing for the U.S. President in 1844 (Toll 31). Given the limitations of the era's technology, cultural trends typically spread slowly, so the rise of minstrelsy was exceptional. Minstrel troupes soon became regular entertainers at the White House, performing for Presidents Tyler, Polk, Fillmore, and Pierce (Toll 31).

The growing public demand led to a surge in the number of minstrel bands. However, exact numbers are difficult to determine due to the lack of consistent records and the fleeting nature of the many small, amateur groups that quickly formed and dissolved (Toll 31).

During the California Gold Rush in 1848, five professional minstrel troupes had established themselves in San Francisco by 1855 (Toll 31). Groups often appeared anywhere with a dense population and accessible transportation - along the Mississippi River, in the rapidly industrializing Northwest, and in the growing cities of the Northeast (Toll 31). Still, only a few well-known troupes managed to tour nationally. One prominent example was Buckley's New Orleans Serenaders, who travelled as far as California, along a tour stopping at Baltimore, Louisville, Savannah, Charleston, Mobile, Memphis, New Orleans, and back again (Toll 31). In fact, far more common was for groups to settle down and perform regular shows in one city or state. Buckley's group did exactly this in 1853, leasing a theatre in New York, and renaming it as Buckley's Opera House (Internet Broadway Database). This lasted nearly ten years, until the passage of the Concert Hall Act in 1862, which prohibited the sale of liquor in theatres, led to its closure.

Minstrel productions sold millions of tickets (Toll). For many these performances represented their first time "meeting" a Black person. Scores of gullible audience members, given the rarity of African Americans in the North, believed that the costumed minstrels were real African Americans (Toll 38). Even Al G. Field, who would later become a minstrel producer and performer, believed, on his first few visits, that the performers were really black (Toll 38). Minstrels took different approaches to this, at times stressing their use of make up, while at others emphasizing the authenticity of their material (in reflecting 'black traditions') and enjoying the confusion (Toll 38). During their tour in 1846, the Ethiopian Serenaders were even initially arrested when it was discovered that they were not real African Americans (Toll 38).

These initial perceptions were important. Slavery was becoming an increasingly important topic of debate, despite Northerners having little or no direct experience of the people involved (Toll 34). As a result, minstrelsy shifted its focus from characters like Zip Coon to songs, dances, and skits that were designed to showcase their "knowledge" of Black people (Toll 34). Northerners wanted to solidify their belief that African American slaves were the complete antithesis to white Americans (Toll 38). Minstrel troupes began focusing on exaggerating "peculiarities" and to further appeal to the public, groups took on names such as Buckley's Congo Melodists" or "Gavitt's Original Ethiopian Serenaders" (Toll 34). Acts were titled "Virginia Jungle Dance," "African Sailor's Hornpipe," and "Nubian Jungle Dance" (Toll 34). Anything that was below the standard for White people was considered/thought to be authentic (Toll 34).

By the late 19th and early 20th centuries, Black performers had entered the minstrel tradition, forming their own troupes and participating in a genre that had originally mocked their identity (Comer). Despite being African American, these performers were still expected to wear blackface makeup and perform exaggerated, racist caricatures that catered to white audiences (Berry). Black minstrels often had to conform to the same stereotypes as their white counterparts, portraying roles like the lazy servant, the dim-witted fool, or the overly musical entertainer (Berry). This allowed them limited entry into the entertainment industry but at the cost of reinforcing degrading images of Black people.

Minstrelsy and Race Relations

Black stereotypes came to symbolize the freedom workers had given up in submitting to industrial discipline, making minstrel shows a popular outlet for American citizens to relieve frustrations with the intense work culture and find entertainment in the leisurely behavior of Black caricatures (Roediger). Though the White audiences and actors found enjoyment in these shows because of their ridicule of Black people, they also experienced a sense of jealousy or longing for this fictional representation of freedom. The transformation of White stereotypes, like the word “coon” used as an insulting description of rural White people, into a slur against Black people, demonstrates how these blackface minstrel characters were also nostalgic for audience members who, in the face of factory discipline, missed being able to act unrestrained (Roediger).

Minstrel songs eroded some of the inequities between the different statuses of Europeans, as discussed in the case of the Irish, and created a unifying common ground of “Whiteness.” Songs that mocked and dehumanized African Americans created a common enemy for Europeans. This new hierarchy blurred the lines between Europeans and established the possibility that White people were equal because they were all socially above African Americans.

To appeal to a larger crowd, minstrels increasingly used songs from other European backgrounds, with “Irish nationalist songs, [taking] their places alongside Tyrolean warbling, yodeling, and Italian and Bohemian Opera” (Roediger). Minstrelsy allowed for an “extreme cultural pluralism” which became whiteness (Toll 271).

Most importantly, minstrelsy drew a sharp divide between “Blackness” and “Whiteness.” This racial dichotomy established the idea that Black people were intrinsically inferior and therefore could never become or do anything that was considered “White” successfully. To achieve this, minstrelsy frequently described black Americans attempting to imitate “White” styles of dress or habits. Lee offers the example of the song “De Color’d Fancy Ball,” where the minstrel performs the waltz “and even tries to speak some French, demonstrating his ‘sophistication’” (Lee). Yet his performance is unconvincing, his French ultimately incomprehensible. That minstrelsy, itself transracial, was parody, only served to further confirm that crossing racial boundaries could only be seen as humorous (Lee).

Minstrelsy & the Jim Crow Laws

Minstrelsy’s promotion of racial stereotypes was a trigger for the Jim Crow Era — a new era of racial discrimination and White supremacist ideology. Created by Thomas “Daddy” Rice in 1828, Jim Crow was the first minstrel character. Rice had seen a Black, possibly disabled black, man singing a similar song to himself. Inspired, he produced not only a song, but an exaggerated character, in which he performed onstage (Library of Congress). The song depicted Jim Crow as a dim-witted and lazy African American slave who, while working on a plantation, stole from others and was deceitful (Lemons). Jim Crow became a recurring minstrel character, adapted by many subsequent minstrel shows, and was used as a derogatory term for African

Americans much like the slur “coon” (Holloway).

By the end of the 19th century, the name Jim Crow was also used to refer to discriminatory practices and laws that restricted African Americans’ rights. Jim Crow laws required segregation between White and Black people for public facilities such as water fountains, restrooms, stores, schools, and housing; as well as separate seating in restaurants, transportation, and theaters.

These laws were an adaptation of the Black Codes, earlier laws used by former confederacy states “intended to limit the new freedom of emancipated African Americans by restricting their movement and by forcing them into a labor economy based on low wages and debt” through incarceration. For instance, Louisiana’s implementation of the Separate Car Act in 1890, soon replicated by other Southern states, including Alabama, Mississippi, and Texas, “requir[ed] all railway companies carrying passengers [...] to provide equal but separate accommodations” by race, seating “passengers to the coaches or compartments set aside for the use of the race to which such passengers belong” with penalties against railroad companies and passengers who violated this act (Boyd).

This act was advertised as legislation enacted “to promote the comfort of passengers on railroad trains,” but in actuality was created to establish racial divide and to prevent either race from interacting with each other (Social Welfare History Project). Though the Separate Car Act specified for the seating in both the Black and White compartments to be equal, Black services were in reality of lesser quality—a phenomenon not limited to transportation segregation, but applicable to all areas of American society divided by racial segregation. Such legislation celebrated the idea of a society in which races were officially “separate but equal”, but in practice amounted to little more than white supremacy (Murray).

The Supreme Court’s 1896 ruling on *Plessy v. Ferguson* that racial segregation was not a violation of the 14th Amendment, affirmed the legality of this legislation, spurring a new wave. Indeed, “separate but equal” policies were promoted to such frequency that the National Association for the Advancement of Colored People (NAACP) in 1951 had a section in their constitution dedicated to denouncing the “‘Separate but equal’ theory” and specified that the “policy of the [NAACP]” is “opposed to racial segregation” and will “refrain from [...] seek[ing] to secure ‘equality’ within the framework of racial segregation,” through “complete integration in education, public housing and other public facilities” and “the abolition of the jim-crow school” system (Murray).

The NAACP additionally condemned radio and television shows that, like minstrel shows, depicted Black people “in a stereotyped and derogatory manner,” arguing that such portrayals “tend to strengthen the conclusion among un-informed or prejudiced peoples that N****es and other minorities are inferior, lazy, dumb and dishonest,” preventing progress towards racial equality (Murray).

Minstrel characters like Jim Crow promoted racial stereotypes that proved lasting. While minstrels may have used offensive and exaggerated characters to entertain, governing politicians, especially in former confederate states, were cognizant of the fact that “if white people accepted

these stereotypes, it [would] become that much easier to deny African Americans the full rights of citizenship,” with popular entertainment media such as theater, radio, and television programs operating as an accessible and easily controlled broadcaster of stereotypes (National Museum of African American History and Culture).

Conclusion

Minstrelsy perpetuated racial inequality by popularizing stereotypes of nationalities which constructed an oppressive social hierarchy. In a time when American culture was in the beginning of developing its defining characteristics, minstrelsy created a commonality between White people at the expense of “Blackness.” This is critical - it was not inevitable that African Americans were seen as subordinate, as the vulnerability of other immigrant groups and the lack of an idea of whiteness demonstrates. Minstrelsy’s hateful messages directly influenced the Jim Crow laws passed at the end of the 19th century, creating a system of oppression against Black people.

The abolition laws did not end either blackface or racial discrimination. Numerous American colleges had blackface troupes, at least as late as the 1950s. In 2004, blackface was still a regular feature of college parties, at least at Georgia State University (Fausset and Robertson). This is unsurprising - it was a regular feature of one of the most famous nightly comedy shows - Saturday Night Live - at least until the early 2000s (Andreeva).

Nor should we be confident about the status of the law. The use of language like “welfare queens” by Reagan has been widely interpreted as the polite face of continued discrimination against African Americans. Almost as soon as the civil rights act was passed, seeking to restore African Americans' rights and political power, states began to mobilize to diminish the impact of the votes of African Americans. The past five years have seen an acceleration of this trend, with states redrawing maps and imposing requirements for identification (Center). Perhaps most worryingly, the Trump administration has reportedly sought to resurrect segregation, with the National Institutes of Health notifying employees that prohibitions on segregated facilities or regulation about equal opportunity “will not be considered when making award decisions or enforcing requirements” (Brown).

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What Are the Different Sources of Sensory Information? How Is This Information Encoded by Animal Sensory Systems, and How Do They Use These Tools to Communicate?

By Angelina Tuminelli

Abstract

No matter the species, all animals must communicate to survive. Because of this, understanding how animals communicate is key to understanding these complex creatures. This literature review summarizes numerous articles detailing five main subtopics that comprise animal communication: the sources of sensory information, how this information is encoded, how animals signal to each other, potential trade-offs of communication, and the multimodal signals that animals can use. In researching these articles, there are two main takeaways to be drawn. The magnetoreception ability of an animal to detect magnetic waves is a highly valuable source of information, but it is a quite understudied area; the second is that while animal communication might seem trivial, researching animals is more beneficial than it seems. In animal research, both humans and animals can benefit. With the appropriate knowledge, humans can better care for animals and learn from them to improve the lives of humans.

Introduction

Communication in animals is a process involving signalling between a sender and receiver, which results in a perceptual response in the receiver, who extracts and encodes information using its specific sensory system from the signal (Stevens, 2013). Depending on the type of source, the receiver's different sensory streams encode this information, potentially influencing the receiver's response (Stevens, 2013). Animal communication is vital to the survival and reproduction of many species and underpins processes such as predator avoidance, foraging, mating, and so forth (Ayasse et al, 2001). Animals have many different processing systems for different stimuli: visual, auditory, olfactory, electric, magnetic, and vibrational, and with further research, scientists may be able to discover even more sensory systems that animals may possess. Researchers have conducted a wealth of studies on the different aspects of animal communication, including their different sources, how they're encoded, and their tradeoffs. To understand animal communication as a whole, it is vital to combine all that knowledge. The key question remains: what are the different sources of sensory information, how is this information encoded by animal sensory systems, and how do they use these tools to communicate? This paper examines how different sources of sensory information- some of which may be multimodal- influence encoding and communication. After the animal encodes the information, it sends a signal back to communicate with the sender. It is important to note that there are tradeoffs to this communication, though. By connecting each of these sections, this literature review details how animals communicate in a comprehensive, process-driven framework. Those whose research aligns with the topics in this paper will benefit greatly from reading this literature review, because this paper is an amalgamation of dozens of different, separate sources from

research sourced from the internet. This paper will empower scientists to take a sensory ecology point of view when exploring questions of how animals use information to communicate.

Review of Literature

Sources of Sensory Information

Understanding the different sources of sensory information used for communication is vital to understanding the entire communication process. It is impossible to understand the output without being knowledgeable about the input. Visual information is defined as light reflecting off different surfaces, and animals often communicate visually by using gestures or body language. Olfactory communication is when animals use scent to communicate (Wyatt 2014). Animals can communicate audibly using sound waves (Schiltz 2022). Animals can communicate with electric information, which comes from static electricity that animals produce (Lissmann 1951). Vibrational communication uses sound waves, which is similar to auditory communication, but not identical: vibrational signals travel through a solid medium. The last source of sensory information that animals might use for communication is magnetic signals. However, magnetic signals cannot be produced by animals- at least, not that humans know of. That being said, animals can detect magnetic waves from the earth (Phillips 1996). The reception of sensory information, including electroreception, magnetoreception, and vision, is a specific, useful example to demonstrate various sensory stimuli. In 1917, Scientists Parker and Van Heusen discovered that animals could indeed sense electrical waves. They did this by presenting a catfish with both a glass and a metal rod. That catfish did not react to the glass rod, but swam away from the metal rod from which electrical waves emanated. For humans, this ability would be very useful, should technology ever replicate it. For example, loose electrical cables are a hazard after hurricanes. Being able to detect that electricity before refugees ever come into contact with it would be very useful. Another article discussing animals' response to sensory stimuli is when Wiltshko et al (1960) tested birds' abilities to fly using magnetoreception. Though magnetoreception and vision are different types of sensory stimuli, this experiment made it clear that they are related. While not thoroughly understood yet, magnetoreception relies on light waves that enter the sensory system through a bird's eyes (Stapput et al, 2010). Aside from certain birds, most other animals receive magnetic waves through little pieces of metal in their beaks or noses (Mouritson, 2013). Magnetoreception is an understudied area compared to the other facets of animal communication. This fact is unfortunate when considering all the possible uses humans have for magnetoreception as a skill and tool for the advancement of technology. An ideal next step for research in this area would be to concentrate studies around the eye and figure out the specific mechanisms in the eyes and brain that conduct magnetoreception. The previous paragraph discussed the electric waves emitted by a metal pole, and the wavelengths of light birds use to not only see, but also navigate. These different sensory information sources -specifically electrical, magnetic, and visual- impact the subsequent steps of animal communication: specifically how information is further encoded and used for communication. A

better understanding of these differences between information sources is vital to understanding animal communication as a whole to benefit humans and animals. An example of a benefit of understanding sensory stimuli is to maintain healthy boundaries between animals and humans domestically and in nature.

Encoding Sensory Information

Understanding the different ways animals encode sensory information is also crucial to understanding animal communication as a whole. When encoding visual information, the eye converts electromagnetic waves into electrical signals that form an image (Passaglia et al, 2004). Scent particles are encoded into animals' brains by oscillating neurons that turn those particles into electrical signals (Laurent and Davidowitz, 1994). Auditory information is encoded by animals' sensory systems when sound waves travel into the ear to the cochlea and turn into electrical signals that go to the brain (Zwislocki, 1962). Electrical stimuli are encoded through electroreceptors that intercept the electrical signal, then send that signal to the brain (Gregory et al, 1989). Not all animals have electroreceptors, so this ability is very specialized (Hopkins, 2010). All animals can feel vibrations, but some animals have specialized hairs that can detect vibrations, which then send signals to the brain (Dusenbery, 1992). There is speculation about how animals detect magnetic waves, but it is not entirely understood how this process works. Animals can use magnetic waves like a compass, which they then can use to migrate or simply get around (Phillips, 1996). Specifically, the processes of electroreception and vision demonstrate the key differences between these two methods of encoding sensory information and how this impacts animal communication. These findings are significant because understanding each sensory system and animal possesses is key to understanding animal communication as a whole. An example of animals encoding information is a study where researchers analyzed the different signature pheromone mixes of bees, and how the bees encode different signature pheromone mixes in order to recognize and communicate with each other (Wyatt et al, 2010). Another example of encoding is when scientists, specifically Kalmijn, studied a spotted dogfish that was able to find a flatfish by encoding the flatfish's electrical cues alone. The dogfish did not use any other senses. A visible pattern in many observations of animals is that researchers only observe one taxon of animal in their specific studies. While information about that animal and how it behaves is important, observing other taxa of the same animal in the same, or similar experiments can yield much more information (Kalmijn et al, 1971). These different examples of animals encoding sensory information, including electroreception and vision, allow scientists to gain a better understanding of the different mechanisms used to encode information and how it ultimately impacts animal communication.

Signalling

The different sources of sensory information and how they are encoded impact how animals use these signals to communicate. Animals can signal to each other visually in many ways (Frisch, 1967). For example, dogs use their eyes to signal distress, birds can dance to try to

attract a mate, and squirrels can use their tails to warn their friends of predators (Gaunet, 2011). A few examples of olfactory signals are when cockroaches release pheromones while mating, or when skunks spray predators if they feel threatened (Medill, 2010). An example of an auditory signal dogs use to communicate is when they bark. They bark to communicate agitation, joy, excitement, et. cetera (Mikkola et al, 2021). An example of the use of electrical signals is when electric eels strengthen their electrical field to intimidate other fish into keeping away (Stoddard, 2009). This myriad of shallow examples is good to grow an understanding of the signals animals use to communicate, but more elaborate examples are necessary to go in-depth. An example of vibrational communication is when fiddler crabs use their pincers to communicate. With their pincers, they pound on the ground to send vibrations to their intended recipient (Aicher and Tautz, 1990). This system of communication is very elaborate- they have different frequencies for mating, fighting, and other forms of communication. Another example of animals using signals in communication is shown in a study on vocal recognition in free-range vervet monkeys (Cheney and Seyfarth, 1980). Cheney et al ran an experiment in which monkeys were tested to recognize their young, and indeed they did. The results of this experiment show the intricacies that comprise audible communication, and the importance it has in keeping monkeys and other animals safe, so that they eventually grow up and reproduce. (Cheney and Seyfarth, 1980). Understanding the complexity of the monkey language and that of other animals is an ideal next step to studying animals. Though unrealistic, this understanding is the next step in fully understanding these creatures. These articles are both examples of how animals use signals in communication, which allow a better understanding of how different sources of sensory information and how they're encoded will impact any animal's communication as a whole. Understanding how animals perceive different stimuli is key to understanding animal communication. When a scientist understands how the sensory system of an animal works, only then can they start to help that animal, understand what they need, and appropriately study that animal.

Tradeoffs of Animal Communication

Animal communication is not always straightforward, and sometimes involves balancing tradeoffs. A tradeoff is a potential drawback of communicating using a certain medium or the consequences of communicating in a certain way. A tradeoff to communicating visually is that an animal becomes more visible to predators and competition, as well as the recipient of that animal's signal (Smith and Harper, 2003). The tradeoffs of olfactory signalling are that odor does not travel very far, and it disperses quickly (Rinberg et al, 2006). A tradeoff of auditory communication is that animals must be louder than their surroundings to be heard, which can be very draining (Stevens, 2013). Not all animals can detect the electricity that they, or animals around them, produce, suggesting that there are significant tradeoffs to this form of communication. One of these tradeoffs is that a predator that can detect the electricity a prey animal gives off, even if the prey can't, usually leads to an unanticipated death. A key tradeoff of using vibrational communication is that it only works when the sender and receiver are using the

same physical medium. Tradeoffs of using magnetoreception are that it cannot be used in communication because animals can't produce these kinds of waves, and can be easily disturbed by other metal objects. One more specific example of a tradeoff when communicating is being the loudest animal. Singing louder requires a lot more energy, wears animals out much faster, and leaves them more vulnerable to potential threats and predators. (Gillooly and Ohpit, 2010; Opgir et al, 2010; Reinhold et al, 1998; Hasselquist and Vensch, 2008). Animals that rely on, or partially rely on, visual signals to attract mates or communicate are also not free from consequences. For example, some birds have bright colors derived from the carotenoids in their diet (McGraw, 2006). Carotenoids can also function as antioxidants, so birds can be at risk if they cannot get enough food to be both full and healthy, and also can attract a mate (McGraw, 2006). As well as the risk of being malnourished, being extremely bright and striking makes a bird more noticeable to predators (Fatouros et al, 2005). These key examples of tradeoffs in animal communication are excellent demonstrations of the balance animals must find between ensuring their signals reach receivers without compromising their ability to survive and reproduce. This complexity of signalling further improves scientists' overall understanding of animal communication and why it's important. Understanding how animals balance risk and reward is extremely important in understanding how they function and how their brains work.

Multimodal Signalling

Lastly, this review will address a phenomenon known as multimodal signalling-communication that involves two senses. A few examples of multimodal signalling are when bees release a pheromone and buzz rapidly to alert friends of danger; when monkeys bang branches together to alert other monkeys of danger while crouching, raising their eyebrows, or opening their mouths (Cheney and Seyfarth, 1990); when tigers mark trees with urine and scratch marks to mark territory (Carter et al, 2015); or when male frogs call to females, and they expand their vocal sacs to showcase their bright colors (Gomez et al, 2009). A more fleshed-out example of multimodal signaling is when Marples et al. conducted a study on whether quails would avoid ladybirds by interchanging their various signals to stay away. The researchers concluded that while color, taste, and smell were able in deterring the quail, those three traits together were the best at deterring the birds from eating the ladybirds. Another example is when Kilber et al observed how warbler chicks displayed their different levels of hunger. They did this by their chirping and opening their mouths; how open the chicks' mouths was determined how hungry they were (1997). Many animals communicate with multiple forms of sensory stimuli, not just one. To better understand the implications of how and why animals communicate in the ways they do, understanding multimodal communication is key. An example of how this helps animals is for conservation efforts. At first glance, animals may look like simple creatures, however, neglect born of ignorance is not the way to help animals not just survive, but thrive. Understanding these examples of multimodal communication is key to understanding not only the different ways animals communicate but animal communication as a whole.

Conclusion

Understanding animal communication is essential because communication is vital to a wide range of animal species for survival. Specifically, the different aspects of animal communication are all significant in understanding how animals communicate. This literature review has compiled research conducted on each topic into a comprehensive framework that interlinks all topics. There are many things people can learn from studying animal communication, for example, how animals balance risk and return when communicating with each other. The value in this paper is that it is a general overview of how animals communicate, it explains the need for certain areas of animal communication to be further studied, and it explains the next steps that can be taken to further understand animals, how they communicate, and how this information can benefit humanity.

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How Does Participation in Sports Influence Critical Thinking in Adolescents, and Which Sports Are Most Effective in Developing These Skills? By Abdul Moez

Running Title

Sports and Critical Thinking in Adolescents

Abbreviations

1. BDNF – Brain-Derived Neurotrophic Factor
2. IQ – Intelligence Quotient
3. APA – American Psychological Association
4. JAMA – Journal of the American Medical Association
5. ISSP – International Society of Sport Psychology
6. PLOS – Public Library of Science

Abstract

As adolescents today have to deal with complex situations where independent decision-making, analysis, and evaluation are essential skills, the development of critical thinking becomes crucial for adolescents. Sports and aerobic exercise can help develop these skills in adolescents

This review is more focused on how sports help adolescents foster these skills and which sports are most effective in developing them. The neurological benefits of aerobic sports are: cognitive flexibility, working memory, inhibitory control, increased levels of BDNF(brain-derived neurotrophic factor), which improves neuroplasticity and decision making, and increases dopamine production. Research shows that athletes have better evaluation skills. Athletes usually have better analytical and evaluative skills because they have to constantly make new routines, deal with pressure, strategies, adjust, and analyze their previous games. Sports can be a more beneficial alternative to technology for adolescents in their free time. Sports participation can have drawbacks, such as burnout, early specialization, injuries, time management, and the mindset of their parents, but these challenges can be overcome by introducing proper routines with compulsory rest days, medical care, time management workshops, and, most importantly, introducing sports facilities in schools.

Different sports can have different benefits as far as critical thinking is concerned. Open skill sports(sports requiring rapid responses in unpredictable environments) and sports that require more physical engagement prove to be more beneficial than close skill sports, such as swimming, running, and gymnastics, and sports that don't require much physical engagement. But different sports foster different branches of critical thinking.

Introduction

Critical thinking skills are vital for adolescents today, from the challenges they face in their classrooms to their social lives. Critical thinking helps them analyze information, make

independent decisions, and solve their daily life and long-term problems. As adolescents have to face more challenging academic environments every day, their ability to think critically not only helps them in their academics but also improves their emotional regulation and communication (Facione, 2011). Research by Halpern (1998) indicates that early development of critical thinking improves flexibility, allowing teens to adapt to new situations, question assumptions, and approach challenges with logic and originality. In today's world, where adolescents have to face peer pressure and exposure to misinformation, critical thinking plays a vital role for them to make original decisions based on their own thinking. Moreover, critical thinking helps adolescents with learning new concepts for the rest of their lives. It also fosters their leadership skills. (Abrami et al., 2015). Research shows that these skills can be fostered in adolescents through sports participation.

Methods

The method used in this study is a literature review. Relevant articles and academic papers were collected using databases such as Google Scholar, PubMed, and ResearchGate. The inclusion criteria were studies involving adolescents aged 13–19 that focused on sports participation and cognitive or critical thinking outcomes.

Results

Cognitive Mechanisms and Brain Function

Participation in sports has been shown to improve aspects of critical thinking, such as cognitive flexibility, working memory, and inhibitory control (Tompson et al., 2008). These are core factors of critical thinking. Sports that challenge athletes physically, in particular, increase levels of brain-derived neurotrophic factor (BDNF), which enhances neuroplasticity and strengthens decision-making centers in the prefrontal cortex (Erickson et al., 2011; Pesce et al., 2009). Physical activities enhance cognitive function and memory by promoting hippocampal growth by 2% (Erickson et al., 2011). Physical activity also increases dopamine and endocannabinoids, improving focus, memory, and learning (Tompson et al., 2015; University of Geneva study). Research also suggests that improvements due to sports may vary by gender. Female athletes may show stronger self-regulation and verbal reasoning skills, while male athletes tend to show higher spatial reasoning abilities (Jacobson & Matthaeus, 2014). These results show that different aspects of critical thinking are fostered due to sports, depending on gender.

Decision-Making and Problem-Solving

Sports require real-time problem-solving pressure. Adolescents involved in sports scored significantly better in problem-solving tests, indicating that they have better problem-solving skills. The athletes also showed greater confidence and evaluation skills compared to non-athletes (Blumenstein & Orbach, 2012; Heppner & Petersen, 1982). Cox (1998) further

supports this, noticing that young athletes have improved focus and self-regulation. A study involving 600 students aged 14–17 used the Problem Solving test developed by Heppner and Petersen (1982) to assess and compare cognitive ability between athletes and non-athletes. The results showed that athletes, especially those who competed at national and international levels in sports, had better evaluative skills and were more confident as compared to non-athletes. These improvements were reflected in the test scores, with performance differences estimated to be approximately 5% in evaluative skills and 6% in self-confidence. (These percentages have not been explicitly stated in the paper; however, they were deduced to give readers a better understanding.)

Development of Metacognitive Skills

Adolescents who frequently participate in sports have to test and analyze their own performances and figure out the next steps to improve their game; they also have to deal with failure many times over their careers—this habit of facing defeat, analyzing your game and coming up with creative methods ways and schedules are essential elements of metacognition and reflective thinking (Cox, 1998). This enhances our ability to think critically beyond athletic contexts, which is why athletes are typically better at critical thinking.

Psychological Theories and Learning

- **Self-Determination Theory** (Ryan & Deci, 2020): Sports enhance intrinsic motivation, which promotes their creativity and analytical thinking.
- **Social Learning Theory** (Bandura, 2018): Team sports often put athletes under high pressure and an environment that improves their decision-making, observational learning, and strategy adaptation.
- **Achievement Goal Theory** (Dweck, 2019): Since athletes face more defeats than wins, they develop evaluation skills since they know how to analyze their defeats and mistakes and make strategic and original plans to improve and win the next time. This fosters their critical thinking skills and not only helps them in their sports career but also in their practical lives.

Long-Term Cognitive Benefits

Studies have confirmed that adolescents involved in regular physical activity have better memory, cognitive flexibility, and larger hippocampal volume (Chaddock-Heyman et al., 2014; Roig et al., 2013). Sports also improve discipline, time management, and resilience, indirectly strengthening critical thinking over time (Duckworth & Seligman, 2017).

Digital distractions vs sports

Another emerging concern is the growing competition between digital distractions and physical activity. Excessive screen time has been shown to affect attention span, critical thinking development in adolescents, and many other important skills, suggesting that promoting sports as an alternative is not only beneficial but necessary in today's digital world (Twenge & Campbell, 2018).

Potential Drawbacks and Cautions + their solutions

Despite its benefits, sports participation in adolescents has its drawbacks, which can lead to several challenges that can hinder critical thinking and academic development:

1. Time Constraints and Academic Stress

Strict training schedules can lead to athletes getting less time to study, which can cause their academics to go down. This can pose numerous problems in their lives, both in the present and later on. (Pinto-Escalona et al., 2022).

Solution: Constantly advise them on time management and monitor their academics to ensure their routine and training are not interfering with their academic progress and academic support programs, particularly for student-athletes.

2. Overtraining and Cognitive Fatigue

Lack of recovery can impair concentration, memory, and executive functioning (Singh et al., 2012).

Solution: Introduce training schedules that allow them to have enough time to rest, mandatory rest days, and emphasize the importance of sleep and recovery.

3 . Psychological Stress and Burnout

Competitive pressure can lead to anxiety, depression, and reduced academic motivation (Yang et al., 2024).

Solution: Provide access to mental health professionals and reduce performance pressure, and train them on how to deal with pressure.

4. Injuries and Cognitive Disruption

Sports-related injuries, especially concussions, negatively impact memory, attention, and school attendance (Covassin et al., 2024; DeMatteo et al., 2022).

Solution: Provide immediate medical care in cases of emergency, ensure safety protocols, advise other students to play fairly and not too roughly, and offer academic accommodations during recovery from injuries.

5. Early Specialization and Cognitive Narrowing

Focusing on one sport too early may lead to adolescents not trying out a variety of activities and limit the development of abstract reasoning and creativity (Fredricks &

Eccles, 2006).

Solution: Encourage participation in various activities that include both physical and intellectual domains, such as chess, arts, public speaking, and a variety of other activities, including other sports that are not their main sport.

Which sports are most effective for developing critical thinking in adolescents?

Sports that demand strategy, collaboration, and adaptability—like soccer, basketball, and hockey—are shown to be most effective in developing critical thinking (Carlson, Winsler, & Smith, 2020). These team sports constantly require players to make split-second decisions, predict their opponents' moves, and adjust their tactics.

Open-skill sports(sports requiring rapid responses in unpredictable environments) demand constant analysis, evaluation, and rapid decision-making. Team sports such as soccer, basketball, and hockey are highly interactive; they require real-time problem-solving, attention shifting, and strategic plans. Athletes in these sports are consistently challenged to adapt to changing scenarios, enhancing executive functions like cognitive flexibility and inhibitory control (Voss et al., 2010).

On the other hand, closed-skill sports—such as track, swimming, or gymnastics—take place in stable environments with less need for tactical adjustment, thus requiring more practice and discipline rather than critical thinking. Martial arts and tennis, which blend physical precision with strategic adaptability, offer a middle ground, promoting planning and quick judgment.

A study by Vestberg et al. (2012) showed that athletes in open-skill sports scored significantly higher on executive function tests than those in closed-skill sports. This further suggests that open-skill environments are better suited to train the brain for flexible and analytical thinking. These findings support the notion that sports such as football, basketball, and hockey are among the most effective in developing critical thinking skills in adolescents. Moreover, beyond the cognitive demands of specific sports, the amount of physical engagement that a certain sport requires also plays a vital role in the extent to which that sport fosters critical thinking. Physical fitness and the amount of aerobic exercise there is in a particular sport may affect factors that enhance critical thinking skills, such as increased hippocampal volume, enhanced synaptic plasticity, and improved executive function (Hillman, Erickson, & Kramer, 2008).

Team sports such as football, basketball, and hockey promote strategic thinking, working memory, and cognitive flexibility due to their dynamic, fast-paced environments requiring constant situational awareness and real-time decision-making.

Sports that demand sustained aerobic activity, such as soccer, swimming, and long-distance running, are particularly beneficial. Among these, football stands out for combining aerobic exercise with high decision-making complexity, offering both cognitive and physical benefits. A study by Chaddock-Heyman et al. (2014) found that adolescents with higher

aerobic fitness levels had larger prefrontal and hippocampal volumes, correlating with better problem-solving and memory skills.

This intersection of vigorous physical engagement and quick decision-making makes football a sport that enhances critical thinking in adolescents more when compared to other sports. While swimming and running improve cardiovascular health, they lack the tactical variability of open-skill team sports, making them less effective in stimulating real-time cognitive processing.

Various sports enhance different aspects of critical thinking, and no single discipline can be considered superior across all cognitive domains.

In conclusion, while various sports offer distinct cognitive and developmental benefits (Hillman, Erickson, & Kramer, 2018), adolescents shouldn't be pressured and limited to a few sports and should be introduced to different activities and sports; at the same time, they shouldn't be overwhelmed by excessive participation in multiple activities. (Fraser-Thomas, Côté, & Deakin, 2008). (Côté, Lidor, & Hackfort, 2009). This approach not only allows adolescents to discover which activity they are genuinely passionate about but also helps prevent burnout and mental fatigue (Gould & Dieffenbach, 2002). Encouraging autonomy in sport selection fosters enjoyment and long-term commitment (Ryan & Deci, 2020), both of which are crucial for both physical and cognitive growth. Ultimately, allowing adolescents to choose autonomously helps them stick with their sport for longer and dedicate more of their time to it, which can increase the amount of critical thinking skills they can acquire (Eime et al., 2013).

Discussion

School is the perfect place for this since parents don't want to admit their children to clubs, especially when they believe it is distracting them from academics. Moreover, many parents can't afford to admit their kids to special academies and often don't have time to take them there. This is why implementing structured sports programs within schools not only avoids this barrier but also creates an inclusive environment for discovering talent in young children in sports they are good at. After-school clubs, led by qualified coaches and with proper facilities, should be introduced. These programs can monitor time management, stress, and the balance between academics, sports, and other activities in adolescents. To strengthen the effectiveness of these initiatives, periodic parent-school workshops can help educate families on how sports enhance academic and cognitive performance, including critical thinking. Offering a variety of sports will accommodate different interests and promote broader cognitive engagement. Integrating sport-based teamwork or strategy activities into the academic curriculum can further reinforce these skills. Research shows that people don't often carry out actions that require them to do extra effort, admitting kids into academies, taking them there every day, monitoring their progress and also ensuring that the academy is safe means that parents will have to put too much effort into this which can cause most of them to dismiss the idea, this is another reason why sports in schools should be introduced, so that parents don't have to put in extra effort to ensure their kids take part in sports. Finally, regular assessments and evaluations should be conducted to

track students' progress across both academics and psychological well-being, while schools can seek policy support or partnerships for funding and long-term sustainability.

Cross-cultural differences also play a vital role in deciding whether adolescents participate in sports frequently or not. For example, countries with strong school-based athletic systems (such as Finland or Japan) demonstrate higher student-athlete academic outcomes, whereas in regions where sports are luxuries, benefits may be limited to more privileged groups (Bailey et al., 2013). This highlights the need for equitable and systemic integration of sports in education.

Conclusion

Sports improve critical thinking in teens by improving executive function, encouraging metacognition, and making them more mentally strong. However, benefits are maximized in sports that require athletes to make quick decisions, work in a team, and vigorous physical activity. Sports may have their drawbacks, but balance, safety, and rest are key to avoiding them.

Despite the research-backed improvements of sports in analyzing information, making independent decisions, participation in sports might not be so easy for some adolescents. Financial constraints are a significant factor; nearly half of the surveyed families are struggling to afford to provide their children with the facilities to play sports, with costs for activities like hockey ranging from \$4,478 to \$7,371 per child annually. Adolescents who live in low-income households are five times less likely to participate in sports than adolescents in high-income households because of the cost of sports facilities. Parental influence also plays a critical role in whether an adolescent plays sports or not; some parents discourage sports involvement due to concerns about academic distraction, potential injuries, or cultural norms that prioritize education over physical activities. For instance, in certain communities, some traditions don't permit females to play sports, viewing such activities as inappropriate or unnecessary. Additionally, the COVID-19 pandemic because of which sports participation decreased in children aged 10 and 11, which led to decreased confidence and long-term disengagement from physical activities. These factors cause barriers that are hard to cross.

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Stock Prediction Using Different Machine Learning Models By Weston Tayebati



Summary (Abstract)

Stock price prediction is important because it helps investors decrease risks and improve their decision-making skills. The goal of this paper is to evaluate which machine learning models are best at making price predictions based on past open prices. The dataset we used is the past 5 years of open prices of Microsoft. We used training/testing splits and feature/target arrays. The models used in this paper are Linear Regression, Decision Tree, Random Forest, Neural Network, and KNN. The measurement for performance is MSE (mean squared error). The Linear Regression model performed the best overall out of all the models, with the lowest testing MSE of 29.99. The more complex models like the Random Forest and KNN models struggled a lot due to overfitting. We can conclude from these results that machine learning models show potential of becoming effective tools in stock price prediction to make profits higher, and risks lower. In the future, what other data, market indicators, or different models can be incorporated to improve the prediction performance?

Introduction

Stock price prediction can help an investor make the right decision to either buy, hold, or sell with insight on how the stock may perform in the future. By recognizing when a stock has a high chance of increasing in value, an investor can buy the stock before it rises to make more profit. Knowing when a stock will drop in price is also extremely beneficial for investors because they can sell their stocks before they plummet, or they can short the stock. Stock price prediction is also important for companies and investors because it can positively influence their long-term strategies by helping them make choices involving their assets, divestitures, and other investments in general. When accurate stock predictions are made, the true value of stocks are shown and the market becomes more efficient.

The question being addressed in this project is: How accurately can a machine learning model predict a stock price or trend using past data and market indicators? My project will explore how accurately a machine learning model can predict future stock prices. The significance of this question is the fact that stock prediction is important for investors, traders,

and financial systems. Better performance with predicting stock behavior is beneficial because it lowers risk and leads to improvement in decision-making, and machine learning can be helpful because it can easily pick up notable patterns that a human might overlook. One goal of this project is to find out how well machine learning can understand trends to make accurate predictions on a stock's behavior, and which models perform the best. The other goal of this project is to show how AI can upgrade or accompany traditional methods for predicting stock prices.

Accurate stock prediction uses data analysis, statistical models, or machine learning algorithms to anticipate a stock's movement in the future with efficiency and reliability. The significance of stock price prediction is that it helps an investor know when to buy, hold, or sell with confidence. It lowers uncertainty and the chances of losing profit by analyzing trends in the market. Stock price prediction can also optimize profits by helping traders capture gains from price movements by giving them insight on what time is best for entry, and for exit. Another benefit from stock price prediction is that it helps an investor decide how much money they want to invest in each stock, which leads to better diversity in their portfolio (also contributing to less risk), and their money is more unlikely to be placed in a stock that is not going to grow. In addition, stock price prediction gives an edge to any investor over those who use outdated information, or their own intuition. This long list of benefits shows how accurate stock prediction builds confidence and improves financial outcomes.

This paper <https://www.sciencedirect.com/science/article/pii/S2590291124000615> used AI to predict stock prices and discovered that SVM, LSTM, and ANN are used with past closing stock prices and prediction performance as the best way to measure performance. Here <https://ieeexplore.ieee.org/document/10895866> is another paper that also focused on LSTM neural networks to improve the performance of stock price prediction. Deep learning models that are frequently used in stock price prediction were discussed in this paper, <https://pdfs.semanticscholar.org/e612/6126d492ae5e80e7cac5888fafcda4e7cff8.pdf>, such as uni-modal and multi-modal; essentially explaining the details of how these models work and how to utilize them. This paper <https://ojs.stanford.edu/ojs/index.php/intersect/article/view/3031> focuses on how machine learning and NLP-enhanced deep learning models are used for accurate stock price forecasting.

Materials and Methods

First, we import 'yfinance' to get stock market data, pandas to work with data frames, and numpy to create arrays of numbers. We make a ticker to pull a stock's data, in this case, we are using Microsoft. Next, download the past 5 years of daily trading data from this stock, including Open, High, Low, Close, Volume, Dividends, and Stock Splits. This data is stored in a pandas dataframe named `aapl_df`. After that we remove unwanted columns, keeping just Open. Then we create two empty numpy arrays, each with 1,259 available float values, one called Open, and one called Close.

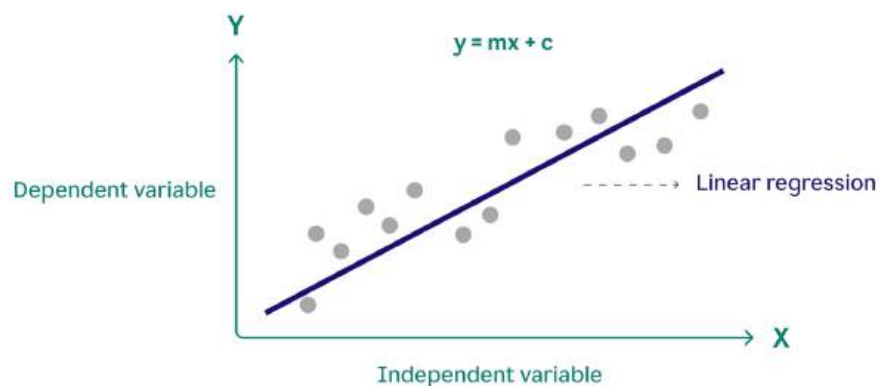
Next, we process our dataset on three consecutive open prices as the input, and then the next day's open price as the prediction.

The next lines split the full dataset into sets: X_{train} , X_{test} , Y_{train} , and Y_{test} . X_{train} is the inputs of the training model (67% of X), X_{test} is the inputs of the testing model (33% of X), Y_{train} is the targets for training (67% of Y), Y_{test} is the targets for testing (33% of Y). We do this to train the model on the X_{train} and Y_{train} data, and then we evaluate its performance on unseen data, X_{test} and Y_{test} , to see how well the model can generalize.

Our goal is to predict the next day's open price based on the past three days' open price. The data comes from Yahoo Finance (for each prediction). We will use five different models, the first being a Linear Regression model (linear model). A linear model predicts output by making a weighted average of the input it is given. Here's an example of what the prediction might look like if we gave it three digits:

$$0.2x_1 + 0.3x_2 + 0.5x_3 + b$$

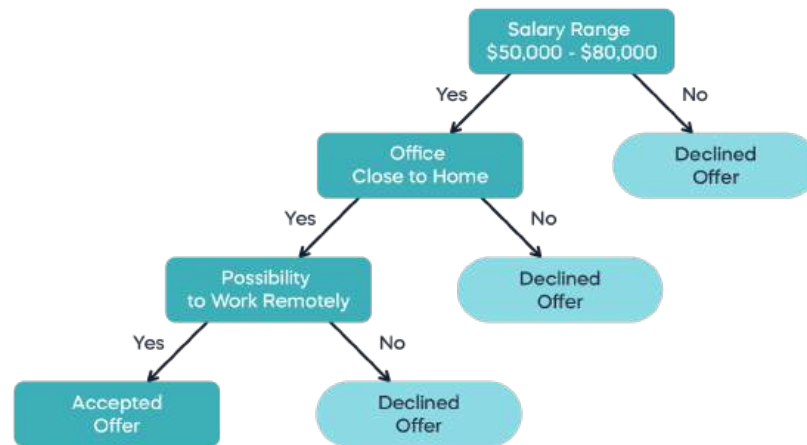
The 'x's in the equation represent the input values, and the coefficients are the weights learned by the model. The term 'b' is used for bias, which helps us shift our prediction up or down. With training, the model learns to adjust the weights to have the best possible performance and to minimize error, so the coefficients in that example are the weights that the AI was trained to find. Linear models perform best when there is a somewhat linear relationship between the input and output (ex. X , Y) and they are quickly trained and clear to interpret. However, they don't perform so well when given a nonlinear variable relationship. Linear models are often used for things like predicting price values and analyzing the stock market but can also be used for other fields like psychology, biology, and sports analytics. Below is an example of a linear model:



Source: Grammarly

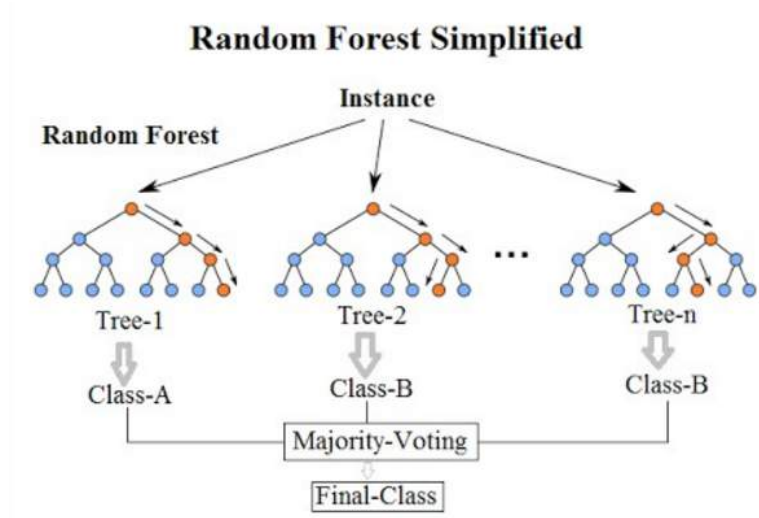
A decision tree is a model that can be thought of as having a flow-chart kind of style. Its 'branches' have the different possible input based decisions, and the 'leaves' at the end of the 'tree' are the output, or final predictions. At each division, the tree decides which input and

parameter to continue with to best separate the data. It continues to divide until it narrows down to a prediction. Decision trees have the hyperparameter of max depth, which means the number of ‘branches’ the tree goes through before making a prediction. Decision trees are easy to picture and analyze, however, they can also be overfitted if the max depth is set too high. Some uses for decision trees in real life are things like medical diagnosis, credit scoring, and segmenting different types of customers in business. Below is an example of a decision tree:



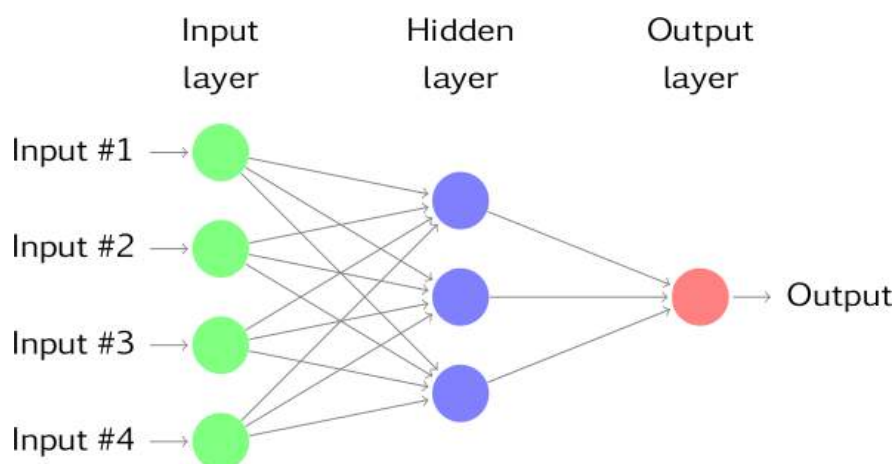
Source: 365 Data Science

A random forest model is a group decision trees that work with each other for reliable and high-performing predictions. Each tree is trained with a randomized dataset, with randomized inputs. They are random to make sure the trees are not in full correspondence to each other. For classification, the model makes a prediction based on popular ‘vote’ from the trees, while regression is based on the average prediction from all the trees. The hyperparameters of a random forest model are the number of trees, max depth of each tree, and the number inputs at each split. Random forests can do well without needing to be manually tweaked and they have good performance when it comes to handling numerical and categorical inputs. Also, the fact that a random forest is a group of trees means it is far less prone to overfitting. These models can interpret non-linear input and output relationships and it can deal with inputs without needing to be overly processed beforehand. Despite these benefits, the output from these models can be more difficult to understand and analyze, and they are computationally costly to run. Some real life uses for random forest models can be medical diagnosis, fraud detection, and customer segmentation. Below is an example of a random forest model:



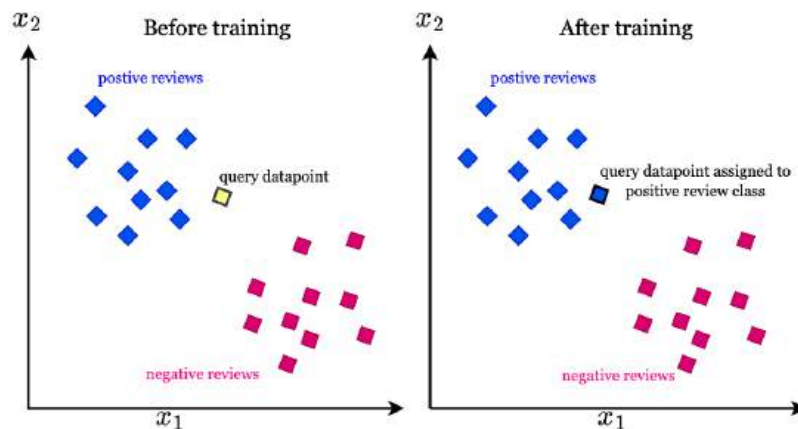
Source: Will Koehrsen - Medium

A neural network is a model with a layered structure that goes as follows: input layer, hidden layers, output layer. There are a number of neurons in each layer, and there are lines called connections that go from one neuron to each neuron in the layer ahead of it. These connections have weights, and the inputs are multiplied by the weights as they go through the connections when moving from one layer to another. Then, all the weighted inputs given to one neuron are then summed up and get passed through an activation function. The training for a neural network starts with completely random weights, and then we use backpropagation (an algorithm that uses learning rate) to improve performance. The hyperparameters of a neural network are the number of hidden layers, number of neurons per layer, the learning rate, and the activation function. Neural networks can deal with scattered, complex, nonlinear relationships, however they require large datasets, they are prone to overfitting, and they are difficult to interpret and analyze. Neural networks can be used for speech and language processing, healthcare image recognition, and finance. Below is an example of a neural network:



Source: OTexts

KNN models are known for “lazy learning” as they don’t use training, they just store all the data and use it directly for predictions. To make a prediction, the model calculates the distance from the new data point to all the other data points in the training dataset, this is called a distance metric. Then, the model finds the ‘k’ training data points, which are the closest points (neighbors) to the new data point. There are different kinds of distance metrics like Euclidean distance, Manhattan distance, and Minkowski distance. For classification, the model goes with the majority decision, and for regression it uses the average of values. The hyperparameters are the ‘k’ value, distance metric, and the choice of weighting neighbors by distance. The KNN model is very simplistic and can deal with clear clusters of data (data points very similar to each other). However, it performs relatively slow on large datasets and can easily have its predictions altered by unrelated inputs and scaling the model. In real life, KNN models can be used for things like handwriting recognition, personal recommendations, healthcare, and finance. Below is an example of a KNN model:



Source: Intuitive Tutorials

After initializing our different models, we set up a backtesting simulation for trading strategies that we come up with based on the predictions from our linear model. We start with \$2,000 and 0 shares. We store the original budget to later calculate the profit, and we store all the predictions made by the linear regression model throughout all of the input data. Next, we loop through 1,240 data points to simulate the management of stocks based on the prediction. There is buy logic which basically means: if the actual Open price is less than the predicted price for tomorrow *and* it is affordable, the simulator buys 1 stock and subtracts its cost from the budget. The sell logic is as follows: If the actual Open price for today is higher than the predicted price tomorrow, the bot sells 1 stock and adds the price (money) to your budget. Then on the last day, the simulator will sell all remaining stock at the current Open price to determine the new budget. Lastly, the simulator will print out the results, which are three numerical values: final cash, remaining stock (should be 0 because you sold all of it), and profit or loss.

Lastly, we try a more aggressive strategy than the previous one, by buying or selling 2 shares at a time. The simulator starts with \$2,000, 0 shares, and a saved original budget to later

determine profit. Again, we are using our trained linear model to predict Open prices and loop through 1,240 days of trading. The buy logic is the same as before, instead with 2 shares being bought in the case that it fits the logic. The sell logic is also almost the same, this time with the requirement of owning two shares before selling two shares, of course. On the last day, the simulator sells all remaining stock to get our cash. Then the profit is calculated, and we print out our results, again being final cash, stocks (should be 0), and total profit or loss.

Overfitting is when a model's mathematics are too complex for the dataset it is given. Symptoms of overfitting are when a model performs well with the training set, but does not perform well when making a prediction using the test set. A model that is prone to overfitting will often learn the training data very well, but have difficulty generalizing and making outputs from testing data that is slightly different from the training set. One way to combat overfitting is to give the model more data. By adding more data, the model uses a more diverse training set and can learn more from it. We can also reduce the complexity of our model by making the hyperparameters smaller. Examples of this could be decreasing the number of layers or decreasing the number of neurons in a neural network. An example of overfitting could be each prediction made by a decision tree with a max depth of 20 on this paper (shown in results), the training MSE was 0 for every company, which shows overfitting.

There are two ways to avoid overfitting, regularization and dropout.

Regularization is when we penalize large weights to train the model to make predictions without relying on 'dominant features' (data points which the model overreferences when making predictions). Penalizing large weights means we add a penalty term to the loss function, essentially telling the model: "Your prediction is only as accurate as your ability to minimize weights". The alpha (λ) parameter controls the strength of the penalty. When the alpha is higher, the model is forced to use smaller weights, which allows for a wider variety of weights being used. The concern with the alpha is that if it is set too high, the model can be underfit. A useful analogy can be investing: just as we also don't want all our money to be in one or two stocks, we don't want the model to base its predictions off of only a few features. Instead, we want the model to make its prediction off a wide variety of features, and in terms of investing, you would want to spread your money out across a diverse selection of stocks.

Dropout solves the problem of the model being too dependent on certain features/neurons. The main idea of dropout is that a certain percentage of the weights are randomly selected to be set to zero. It keeps the model from being reliant on certain features to make its prediction, and forces the model to learn to make a prediction using a wider variety of features. When using dropout, some key features/inputs are left out when making the prediction, but it diversifies the types of features the model uses to make its prediction, reinforcing the model's ability to perform well during testing. It is comparable to having a sports team play a game while their star player sits out, they are forced to utilize their "role players" who may have otherwise been insignificant. This way, when the star player (important features) play in the next game (testing), the role players on the team contribute more, and the team has a higher likelihood of winning (after using dropout for testing, the model will perform better). Dropout prevents

overfitting, and builds stronger generalization for the model even when using complex neural networks.

Results

Mean squared error for each model using 'MSFT' (Microsoft)

	Linear	Decision Tree	Random Forest	Neural Network	KNN
Hyperparameters	None	Max Depth = 2	Max Depth = 2 N_Estimators = 100	Max Iter = 200	N_Neighbors = 2
Testing Mean Squared Error	25.18	732.82	562.69	30.63	36.90
Training Mean Squared Error	29.99	1012.35	783.06	34.34	783.06

Mean squared error for each model using 'MSFT' (Microsoft) with different hyperparameters

	Linear	Decision Tree	Random Forest	Neural Network	KNN
Hyperparameters	None	Max Depth = 20	Max Depth = 20 N_Estimators = 100	Max Iter = 300	N_Neighbors = 10
Testing Mean Squared Error	31.53	57.68	39.13	36.59	250.86
Training Mean Squared Error	26.51	0	4.61	32.13	4.61

Mean squared error for each model using 'NVDA' (NVIDIA)

	Linear	Decision Tree	Random Forest	Neural Network	KNN
Hyperparameters	None	Max Depth = 2	Max Depth = 2 N_Estimators = 100	Max Iter = 200	N_Neighbors = 2
Testing Mean Squared Error	8.20	135.43	111.36	8.28	10.44
Training Mean Squared Error	5.10	107.33	94.40	5.72	94.40

Mean squared error for each model using 'NVDA' (NVIDIA) with different hyperparameters

	Linear	Decision Tree	Random Forest	Neural Network	KNN
Hyperparameters	None	Max Depth = 20	Max Depth = 20 N_Estimators = 100	Max Iter = 300	N_Neighbors = 10
Testing Mean Squared Error	6.72	15.44	8.01	7.90	8.73
Training Mean Squared Error	5.77	0	0.95	6.47	0.95

Mean squared error for each model using 'MCD' (McDonald's)

	Linear	Decision Tree	Random Forest	Neural Network	KNN
Hyperparameters	None	Max Depth = 2	Max Depth = 2 N_Estimators = 100	Max Iter = 200	N_Neighbors = 2
Testing Mean Squared Error	6.61	192.03	119.31	9.55	12.02
Training Mean Squared Error	9.02	214.51	138.18	12.04	138.18

Mean squared error for each model using 'MCD' (McDonald's) with different hyperparameters

	Linear	Decision Tree	Random Forest	Neural Network	KNN
Hyperparameters	None	Max Depth = 20	Max Depth = 20 N_Estimators = 200	Max Iter = 300	N_Neighbors = 10
Testing Mean Squared Error	8.88	19.69	12.60	16.38	72.78
Training Mean Squared Error	7.90	0	1.38	14.55	1.38

Mean squared error for each model using 'SBUX' (Starbucks)

	Linear	Decision Tree	Random Forest	Neural Network	KNN
Hyperparameters	None	Max Depth = 2	Max Depth = 2 N_Estimators = 100	Max Iter = 200	N_Neighbors = 2
Testing Mean Squared Error	2.35	17.22	16.51	2.68	3.54
Training Mean Squared Error	2.77	16.41	15.71	3.20	15.71

Mean squared error for each model using 'SBUX' (Starbucks) with different hyperparameters

	Linear	Decision Tree	Random Forest	Neural Network	KNN
Hyperparameters	None	Max Depth = 20	Max Depth = 20 N_Estimators = 200	Max Iter = 300	N_Neighbors = 10
Testing Mean Squared Error	3.36	6.75	3.90	3.65	18.41
Training Mean Squared Error	2.27	0	0.38	2.56	0.38

Profit (buying or selling 1 stock) using the linear model backtesting simulation

	Microsoft	NVIDIA	McDonald's	Starbucks
\$2,000	\$2,783.15	\$22,441.57	\$1,209.09	\$1,514.26
\$4,000	\$6,089.74	\$40,312.12	\$1,727.78	\$2,497.66

Profit (buying or selling 2 stocks) using the linear model backtesting simulation

	Microsoft	NVIDIA	McDonald's	Starbucks
\$2,000	\$2,582.71	\$24,501.49	\$1,371.50	\$1,519.42

	Microsoft	NVIDIA	McDonald's	Starbucks
\$4,000	\$5,873.27	\$47,783.18	\$1,831.67	\$2,984.46

Discussion

We can infer from these results that machine learning models can be used effectively for stock price prediction. The Linear Regression model performed the best, while the Random Forest Regressor and KNN models both struggled with heavy overfitting. Despite this paper only exploring the models' predictions based on open price, work will be done in the future to integrate a wider variety of data to increase the performance of these models. Our next work will be using high, low, and volume, and close prices, as well as a news sentiment model. The high and low prices will allow the model to understand the stock's volatility, and the closing prices will let the model map out a stock's performance on any given day. Volume will give the model a way to see a stock's activity and popularity, this way it can predict trends and market shifts. Arguably the most important addition to the next paper will be the news sentiment, which will be a Natural Language Processing (NLP) model. It will be used to analyze a specific news source on select days to recognize patterns between the stock price and the news involving that specific stock. We plan to reinforce my stock price prediction system and make it more efficient and accurate by using a more advanced and diverse dataset. In the future we will investigate: How do political restrictions (like the recent tariffs in the U.S.) influence and affect the stock market?

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Advancing Electric Vehicle Design through Lightweight Materials: A Comparative Review of Aluminium, Magnesium, and Fibre-Reinforced Composites

By Aarav Kharbanda

Abstract

As the world rapidly shifts towards electric vehicles, the need for using lighter and more efficient materials in electric vehicle manufacturing has become increasingly important. The chassis makes up a large portion of an EV's total weight, therefore reducing its mass can significantly improve driving range as well as overall efficiency of the vehicle without compromising its safety or structural strength. This review compares three key categories of lightweight materials used in EV chassis design: aluminium alloys, magnesium alloys, and fibre-reinforced composites. Aluminium alloys are already common in the automotive industry because they offer a good balance of strength, corrosion resistance, and recyclability. Magnesium alloys are even lighter, but they often struggle with issues like corrosion and reduced fatigue strength. Fibre-reinforced composites provide outstanding stiffness and strength at very low weight and allow for greater design flexibility; however, they are still limited by high manufacturing costs and challenges in large-scale recycling. The research suggests that the most effective solution for future electric vehicle designs is adopting a hybrid chassis structure strategy that combines the strengths of metals and composites. The review concludes by highlighting emerging advances in material processing, improved recycling methods, and sustainable manufacturing that are making the way for lighter, stronger, and more environmentally friendly EV chassis designs.

Introduction

The global shift towards electric mobility is making automobile manufacturers rethink how vehicles are designed and manufactured. Unlike traditional internal combustion engine (ICE) vehicles, electric vehicles (EVs) must address challenges such as heavy battery packs, heat management, while maximizing overall energy efficiency. One of the most important strategies that automakers use is vehicle lightweighting - reducing the overall weight of the vehicle, therefore improving driving range and acceleration. As EVs depend on stored electrical energy, lowering vehicle weight directly impacts performance and range without the need for large batteries.

Chassis is the main structural frame of the vehicle that ensures strength, crash safety, and it also supports all other vehicle components. The chassis and body together make up roughly 25–30% of a vehicle's weight, hence choosing the right material for the chassis plays an important role in overall efficiency and performance. Traditional steel-based chassis, although strong and cost-effective, are no longer ideal for EVs, as they require higher strength-to-weight ratios, better corrosion resistance, and more environment friendly manufacturing solutions.

These factors have made the automotive manufacturers explore lightweight metals and composites. Aluminium alloys, magnesium alloys, and fibre-reinforced composites have

emerged as leading options due to their ability to significantly reduce weight. For example, replacing mild steel with aluminium can reduce chassis mass by up to 40%, while magnesium can cut an additional 30% compared to aluminium. Advanced composites like carbon fibre-reinforced polymers (CFRP) offer superior strength and stiffness at extremely low weight.

However, selecting these materials involves balancing multiple factors - cost, ease of manufacturing, crash performance, and recyclability. Aluminium has become widely adopted worldwide in both premium and mainstream EVs, while magnesium and fibre-reinforced composites are mostly used in high-end or specialized models because of higher production costs and manufacturing challenges. Finding the right balance between performance and affordability remains a key concern for EV chassis design.

This review examines aluminium alloys, magnesium alloys, and fibre-reinforced composites for EV chassis applications. It discusses their mechanical and physical properties, manufacturing limitations, environmental impacts, and suitability for large-scale production. The review also highlights new developments in hybrid chassis designs and technologies that allow these materials to be integrated into next-generation electric vehicles.

Role of Lightweight Materials in Electric Vehicle Design

Weight reduction remains one of the most effective strategies for enhancing the efficiency and performance of electric vehicles EVs. Unlike conventional internal combustion engine (ICE) vehicles, which compensate for additional mass through larger engines, EVs are constrained by the limited energy density of current battery technologies. Consequently, reducing overall vehicle mass directly improves driving range, acceleration, handling, and braking performance, while decreasing energy consumption. Studies indicate that a 10% reduction in vehicle weight can yield a 6–8% improvement in energy efficiency and extend driving range by approximately 5–7%, without requiring any modification to the battery pack.

The primary engineering challenge lies in achieving weight savings without compromising structural integrity, safety, or crashworthiness. The chassis, which supports critical components such as the drivetrain, suspension, and battery modules, must maintain high torsional rigidity and energy absorption capacity under impact. Therefore, materials selected for chassis construction must combine high specific strength (strength-to-weight ratio), corrosion resistance, durability, and manufacturability.

Lightweight materials such as aluminium alloys, magnesium alloys, and fibre-reinforced composites satisfy many of these design requirements. Aluminium alloys are extensively used in EV frames for their balanced combination of strength, ductility, and recyclability. Magnesium alloys, which are nearly one-third lighter than aluminium, provide further mass reduction potential but are limited by their lower corrosion resistance and fatigue performance. Fibre-reinforced composites, including carbon and glass fibre composites, offer exceptional stiffness and fatigue life while enabling complex geometrical designs. However, their widespread application is hindered by high manufacturing costs and limited recyclability.

To overcome these limitations, modern EV manufacturers are increasingly adopting multi-material chassis designs that integrate metals and composites in structurally optimized configurations. This hybrid design approach enables engineers to assign materials based on performance requirements—metals for high-impact or load-bearing zones, and composites for lightweight reinforcement and stiffness enhancement. Such configurations not only reduce mass but also align with the industry’s shift toward modular, sustainable, and energy-efficient vehicles suitable for next-generation electric mobility.

Aluminium Alloys

Aluminium and its alloys are among the most extensively utilized lightweight materials in electric vehicle (EV) chassis construction due to their favorable combination of strength, low density, corrosion resistance, and recyclability. With a density of approximately 2.7 g/cm^3 , aluminium is nearly one-third the weight of conventional steel, allowing for substantial mass reduction while maintaining high structural integrity and safety performance.

Mechanical and Physical Properties

Aluminium alloys possess high specific strength and excellent formability, making them suitable for both extruded and sheet-metal components in automotive design. Commonly used grades such as 6061, 6082, and 7075 offer varying balances between strength and ductility, depending on the chosen temper and processing conditions. Typical tensile strengths range between 250–500 MPa, while maintaining sufficient elongation to enable effective crash energy absorption—a critical factor in chassis safety performance.

A naturally forming oxide layer enhances aluminium’s corrosion resistance, extending the lifespan of vehicles operating in humid or coastal environments. Thermally, aluminium’s high thermal conductivity ($\sim 235 \text{ W/m}\cdot\text{K}$) supports efficient heat dissipation, which is particularly beneficial in EVs where battery modules, motors, and power electronics generate significant heat. However, aluminium’s lower fatigue strength compared to steel requires careful structural design, especially in high-stress regions such as suspension mounts, joints, and cross-members.

Manufacturing and Joining Techniques

One of aluminium’s greatest advantages lies in its manufacturing versatility. It can be cast, extruded, rolled, or stamped into complex geometries, making it adaptable for both monocoque and space-frame chassis architectures. Innovations such as high-pressure die casting (HPDC)—notably demonstrated in Tesla’s “Giga Casting” approach—allow for the production of large, integrated chassis components that significantly reduce part count, assembly time, and structural weight while improving stiffness.

Despite these benefits, aluminium presents challenges in joining and fabrication due to its high thermal conductivity and rapid oxide layer formation. Conventional welding techniques may reduce mechanical strength in heat-affected zones (HAZs). To address these limitations,

advanced joining methods such as friction stir welding (FSW), laser beam welding, and structural adhesive bonding are increasingly employed to ensure durable, high-strength connections. Mechanical fastening techniques, including self-piercing rivets (SPRs), are also widely used, particularly in multi-material assemblies that combine aluminium with composites or steels.

Applications in Electric Vehicles

Aluminium plays a prominent role in several commercial EV platforms due to its strength-to-weight efficiency and design flexibility. The Tesla Model S and Model X feature predominantly aluminium body structures to optimize performance and driving range. The Jaguar I-Pace employs a bonded and riveted aluminium architecture that provides excellent torsional rigidity and crash protection. Similarly, the Audi e-tron integrates aluminium-intensive suspension components and subframes to reduce unsprung mass and improve ride comfort.

Advantages and Limitations

Aluminium’s combination of lightweight characteristics, mechanical performance, and high recyclability makes it a cornerstone material for sustainable EV manufacturing. Approximately 90–95% of automotive aluminium can be recycled with minimal degradation of material properties, resulting in significant energy and emissions savings compared to primary production. However, the material’s higher initial cost and energy-intensive smelting process remain limiting factors for large-scale, cost-sensitive EV applications. Ongoing research is focused on developing new alloy formulations, enhancing secondary aluminium recycling efficiency, and advancing joining and forming technologies to reduce production costs and environmental impact.

Table 1: Mechanical, manufacturing, and sustainability characteristics of aluminium alloys used in electric vehicle chassis

Property	Performance / Description
Density (g/cm³)	2.7
Tensile Strength (MPa)	250-500
Elastic Modulus (GPa)	69
Corrosion Resistance	Excellent (improves with oxide layer and coating)
Fatigue Strength	Moderate - Good
Crashworthiness	Excellent (absorbs energy via controlled deformation)
Manufacturability	High - supports casting, extrusion rolling, and stamping

Recyclability	Excellent (~90-95% recoverable with minimal quality loss)
Cost (Relative)	Moderate
Key Limitations	Energy-intensive primary production, strength reduction in weld zones
Key Advantages	High strength-to-weight ratio, excellent corrosion resistance, easy to form and weld, and highly recyclable for sustainable EV manufacturing.

Magnesium Alloys

Magnesium alloys represent the lightest class of structural metals currently utilized in automotive engineering. With a density of approximately 1.8 g/cm³, magnesium is about 35% lighter than aluminium and nearly 75% lighter than steel, offering exceptional potential for vehicle lightweighting. Despite these advantages, magnesium's limited corrosion resistance, relatively low ductility, and higher production costs have restricted its widespread application to select components rather than full chassis structures.

Mechanical and Physical Properties

Magnesium alloys typically exhibit tensile strengths in the range of 200–350 MPa and an elastic modulus of approximately 45 GPa, which is lower than that of aluminium (70 GPa) and steel (200 GPa). Although this lower stiffness limits their use in high-load structural regions, magnesium's extremely low density provides a high specific strength, making it advantageous for weight-sensitive applications.

Common automotive magnesium alloys include AZ91D (magnesium–aluminium–zinc) and AM60 (magnesium–aluminium–manganese), both valued for their strength-to-weight ratio, castability, and impact resistance.

Magnesium also exhibits excellent vibration damping capability, an important property for minimizing noise, vibration, and harshness (NVH) in vehicle interiors. This characteristic, coupled with its low rotational inertia, enhances ride comfort and handling precision when used in suspension and steering components. However, magnesium's susceptibility to corrosion, especially in chloride-rich environments, and its relatively low fatigue strength constrain its application in exposed or high-stress chassis zones.

Manufacturing and Processing

High-pressure die casting (HPDC) remains the predominant manufacturing method for magnesium components. It allows precise, high-volume production of lightweight parts with minimal post-processing, making it ideal for instrument panel supports, gearbox housings, and seat frames. However, magnesium's high chemical reactivity necessitates controlled atmospheres and protective coatings during casting to prevent oxidation and surface degradation.

Recent advancements in alloy development and surface treatment technologies—including micro-arc oxidation (MAO) and plasma electrolytic oxidation

(PEO)—have markedly improved corrosion resistance and surface hardness. Additionally, hybrid manufacturing approaches, which combine magnesium with aluminium or polymer composites, are being investigated to achieve a balanced compromise between strength, cost, and durability.

Applications in Electric Vehicles

In electric vehicles, magnesium alloys are increasingly used in non-critical yet weight-sensitive applications. Their low density and excellent castability make them ideal for steering wheels, seat frames, battery enclosures, and transmission housings. Manufacturers such as BMW and Ford have successfully incorporated magnesium castings in interior and substructure components to improve efficiency and handling dynamics.

While a fully magnesium-based chassis has yet to be realized in mass production, experimental projects—such as Mazda’s RX-8 concept and General Motors’ Ultralight Structure Project—demonstrate the feasibility of achieving up to 25–30% weight reduction compared to equivalent aluminium frameworks.

Advantages and Limitations

Magnesium alloys offer an exceptional strength-to-weight advantage, combined with high castability and inherent vibration damping, making them ideal for lightweight, secondary structural applications. However, key challenges persist: poor corrosion resistance, lower stiffness, and flammability risks during processing hinder widespread use. Furthermore, magnesium extraction is energy-intensive and geographically concentrated, limiting economic scalability and sustainability.

Current research focuses on developing corrosion-resistant alloy systems—such as Mg–Ca–Zn and Mg–Al–RE (rare earth) compositions—and protective coatings that can enhance surface durability. These innovations, coupled with improvements in recycling and hybrid manufacturing, are expected to broaden magnesium’s role in future electric vehicle chassis designs.

Table 2: Key properties and performance factors of magnesium alloys for lightweight EV structures

Property	Performance / Description
Density (g/cm ³)	1.74
Tensile Strength (MPa)	250-350
Elastic Modulus (GPa)	45
Corrosion Resistance	Poor (requires protective coatings)
Fatigue Strength	Moderate

Crashworthiness	Low (brittle under impact; limited ductility)
Manufacturability	Good for casting; limited for forming and welding
Recyclability	Moderate (limited by oxidation during re-melting)
Cost (Relative)	Moderate - High
Key Limitations	Poor corrosion resistance, low ductility, limited crash performance, and high reactivity during processing and recycling.
Key Advantages	Ultra-lightweight, high specific strength, good damping characteristics

Fibre-Reinforced Composites

Fibre-reinforced composites (FRCs) have emerged as one of the most promising classes of lightweight structural materials for electric vehicles (EVs) due to their exceptional specific strength, stiffness, and fatigue resistance. These materials are composed of high-strength fibres—typically carbon or glass—embedded within a polymer matrix such as epoxy or thermoplastic resin. The resulting composite structure exhibits mechanical performance comparable to, or even surpassing, that of metals, at a fraction of the weight.

Mechanical and Physical Properties

The mechanical properties of FRCs are highly dependent on fibre type, orientation, and matrix composition. Carbon-fibre reinforced polymers (CFRPs) typically achieve tensile strengths between 600–1000 MPa with a density of 1.6 g/cm³, resulting in an exceptional specific strength and stiffness ratio several times greater than that of steel or aluminium. Glass-fibre reinforced polymers (GFRPs), while more cost-effective, offer moderate strength (300–500 MPa) and a slightly higher density (~2.0 g/cm³).

In addition to their outstanding strength-to-weight performance, composites offer excellent fatigue resistance, corrosion resistance, and design flexibility, making them suitable for aerodynamic, crash-critical, or aesthetic components. However, their brittle failure behaviour and anisotropy demand precise control of fibre orientation and manufacturing quality to ensure predictable structural performance.

Manufacturing and Forming Processes

Manufacturing of FRCs can be achieved through several methods, including hand lay-up, resin transfer moulding (RTM), autoclave curing, and emerging thermoplastic forming techniques. For high-volume automotive applications, RTM and compression moulding are preferred due to their shorter cycle times and consistent repeatability.

Recent advancements in automated fibre placement (AFP) and additive manufacturing (3D printing) of composites are significantly reducing both material waste and production costs. Nonetheless, composite fabrication remains more labour-intensive and costly than metal

forming. Moreover, joining composites to metallic components requires specialized techniques—such as adhesive bonding, bolted joints with inserts, or hybrid mechanical-adhesive fasteners—to ensure load transfer efficiency and prevent delamination.

Applications in Electric Vehicles

Fibre-reinforced composites have been widely adopted by premium EV manufacturers aiming to offset the mass of heavy battery systems. The BMW i3 and i8 utilize CFRP passenger cell structures that provide superior crash safety and torsional rigidity, achieving nearly 50% weight reduction compared to conventional steel bodies. The Porsche 918 Spyder and Tesla Roadster (prototype) also incorporate composite body panels and chassis components to improve performance and aerodynamic efficiency.

Beyond body structures, composites are increasingly used in battery enclosures, aerodynamic panels, and suspension components, where their low thermal conductivity and corrosion resistance offer distinct operational advantages. These applications highlight FRCs' growing role in balancing lightweighting and safety objectives in next-generation EV design.

Sustainability and Recycling Challenges

Despite their performance advantages, FRCs face significant sustainability challenges due to energy-intensive production and limited recyclability. Thermoset composites cannot be remelted or reshaped, making end-of-life material recovery difficult. Although mechanical grinding and chemical recycling techniques are under investigation, they remain costly and inefficient.

Thermoplastic composites, in contrast, offer improved recyclability and repairability, making them a focus for future EV platforms. Researchers are also exploring bio-based fibres (e.g., flax, hemp) and recycled carbon fibres, as well as hybrid metal–composite architectures that combine the strength of metals with the weight advantage of composites. These developments are crucial for enabling sustainable and scalable adoption of FRCs in the automotive industry.

Advantages and Limitations

Fibre-reinforced composites offer unparalleled strength-to-weight performance, design freedom, and corrosion resistance, positioning them as a leading solution for structural lightweighting. However, high production costs, complex joining requirements, and recycling difficulties continue to limit their widespread use. Future innovations in thermoplastic resins, automated manufacturing, and bio-composite development are expected to bridge the gap between performance and sustainability, making FRCs integral to next-generation electric vehicle chassis and body systems.

Table 3: Comparative properties of carbon and glass-fibre composites relative to metals

Property	Carbon Fibre Composite (CFRP)	Glass Fibre Composite (GFRP)	Metals (Reference)
Density (g/cm ³)	1.6	2	2.7 (Al), 7.8 (Steel)
Tensile Strength (MPa)	600-1000	300-500	250-500 (Al)
Elastic Modulus (GPa)	70–150 (anisotropic)	40-80	69 (Al), 200 (Steel)
Corrosion Resistance	Excellent	Excellent	Moderate - Good
Fatigue Strength	Excellent	Good	Moderate
Crashworthiness	Good (progressive failure mode)	Moderate	Excellent (ductile deformation)
Manufacturability	Complex; requires specialized moulding)	Easier; suitable for compression moulding	Mature and scalable
Recyclability	Low (thermoset); Moderate (thermoplastic)	Low - Moderate	High
Cost (Relative)	Very high	Moderate	Moderate
Key Limitations	Brittle failure; difficult joining and recycling	Lower strength than CFRP; limited thermal resistance	Higher density; corrosion susceptibility
Key Advantages	Highest stiffness-to-weight ratio; excellent fatigue resistance	Cost-effective; good mechanical performance	Well-understood processing and repairability

Comparative Analysis of Lightweight Materials for EV Chassis

The selection of materials for electric vehicle (EV) chassis design demands a careful balance between weight reduction, mechanical performance, crash safety, cost-effectiveness, and sustainability. Aluminium alloys, magnesium alloys, and fibre-reinforced composites (FRCs) each exhibit distinct advantages and limitations, making them suitable for different vehicle segments, design philosophies, and production scales.

Comparative Property Overview

Table 4: Comparative analysis of aluminium alloys, magnesium alloys, and fibre-reinforced composites for electric vehicle chassis applications

Property	Aluminium Alloys	Magnesium Alloys	Fibre Reinforced Composites (CFRP)
Density (g/cm ³)	2.7	1.74	1.6
Specific Strength	High	Moderate - High	Very High
Elastic Modulus (GPa)	69	45	70-150 (anisotropic)
Corrosion Resistance	Good (with coatings)	Poor (requires protection)	Excellent
Fatigue Strength	Good	Moderate	Excellent
Crashworthiness	Excellent (energy absorption)	Moderate	Good (depends on fibre orientation)
Manufacturability	Mature and scalable	Limited industrial maturity	Complex; high cost
Recyclability	Excellent	Excellent	Limited (depends on matrix)
Cost (Relative)	Moderate	Moderate - High	Very high
Applications in EVs	Chassis, suspension, battery frames	Steering, seat frames, interior structures	Passenger cells, body panels, battery enclosures

This comparison highlights that while aluminium provides the most balanced performance, magnesium and composites deliver superior lightweighting potential in specific applications but at higher cost or manufacturing complexity.

Weight Reduction Potential

In electric vehicles, every kilogram of structural weight saved contributes directly to improved range, acceleration, and handling.

Magnesium alloys offer the greatest theoretical mass savings—approximately 35% lighter than aluminium and 75% lighter than steel—but suffer from corrosion and fatigue limitations that restrict their use in primary load-bearing structures.

Carbon-fibre reinforced polymers (CFRPs) provide the highest strength-to-weight ratio, enabling up to 50% component mass reduction relative to aluminium. However, high production costs and poor recyclability limit widespread adoption.

Aluminium alloys, while denser, offer the best trade-off between lightweighting, manufacturability, and safety, explaining their dominant role in current EV chassis and subframe systems.

Mechanical and Safety Performance

From a crashworthiness perspective, aluminium extrusions and castings excel due to their ability to absorb impact energy through controlled plastic deformation, ensuring occupant protection.

Composites, in contrast, dissipate energy via progressive failure mechanisms, fracturing in a manner that can be engineered through fibre orientation to tailor crash response. This, however, requires advanced simulation and testing methodologies to ensure reliability.

Magnesium, with its lower ductility and limited strain hardening, demonstrates inferior impact absorption and is thus mainly employed in non-critical or secondary components.

Sustainability and Lifecycle Assessment

Sustainability has become a central factor in EV material selection. Aluminium stands out for its closed-loop recyclability, as it can be remelted indefinitely with only 5% of the energy required for primary production. Magnesium recycling is technically feasible but challenged by oxidation and contamination during re-melting, which limits large-scale reuse. Fibre-reinforced composites, especially thermoset-based systems, remain difficult to recycle due to cross-linked polymer matrices. Nevertheless, the development of thermoplastic composites and bio-derived fibres is gradually improving the environmental footprint of composite materials. In current practice, aluminium remains the most sustainable and circular option, though rapid advances in composite recycling and hybrid materials are narrowing the gap.

Cost and Scalability

Economic feasibility remains a decisive criterion in chassis material selection. Aluminium alloys benefit from mature supply chains, global availability, and process familiarity, making them cost-effective for both premium and mid-range EVs. Magnesium alloys are constrained by limited global production and processing challenges, keeping costs comparatively high. CFRPs, despite their superior performance, remain restricted to high-performance or luxury EVs due to expensive raw materials, tooling, and long cycle times. Future cost reductions in automated composite manufacturing and magnesium alloy processing may expand their use across broader EV segments.

Summary of Comparative Findings

Table 5: Recommended material selection for different electric vehicle segments based on performance, cost, and sustainability criteria

EV Segment	Recommended Material	Justification
Mass Market EVs	Aluminium Alloys	Cost-effective, safe, recyclable, and well-understood manufacturing base
Performance EVs	CFRP Composites	Maximum weight reduction, high stiffness, and

		premium aesthetics
Lightweight City EVs	Magnesium (Hybrid Structures)	Suitable for secondary or interior components with strict mass targets

Overall, a hybrid multi-material approach, combining aluminium and composite elements, represents the most promising direction for next-generation EV chassis. Such designs allow engineers to position materials based on local performance demands—using aluminium for load-bearing safety zones and composites for lightweight reinforcements. This strategy enables significant mass reduction without compromising safety, scalability, or recyclability, aligning with the automotive industry’s broader goals of efficiency, sustainability, and electrified mobility.

Conclusion and Future Outlook

Lightweighting remains a key focus of electric vehicle (EV) design, as reducing vehicle mass directly improves driving range, efficiency, and sustainability. This review compared three leading lightweight material categories—aluminium alloys, magnesium alloys, and fibre-reinforced composites—with respect to their structural performance, manufacturing practicality, recyclability, and cost.

Among the three, aluminium alloys currently offer the most balanced and scalable solution. They provide a strong combination of mechanical strength, corrosion resistance, and design flexibility, while also being highly recyclable and widely available. These qualities explain their widespread use in today’s mass-market EV chassis and body structures. Magnesium alloys, despite offering the greatest potential for weight reduction, are limited by corrosion challenges, fatigue concerns, and higher processing costs, limiting their role mainly to secondary structural components. Fibre-reinforced composites, especially carbon-fibre reinforced polymers, deliver exceptional stiffness and fatigue resistance at extremely low weight, but their high cost and recycling difficulties currently restrict them to premium EVs.

The key takeaway is that no single material can meet every requirement of next-generation EV chassis design on its own. The most promising direction is the adoption of multi-material hybrid structures, where each material is used where it performs best - metals in crash-critical zones, and composites in areas where weight reduction and stiffness are highest priorities. Advances in joining technologies, such as friction stir welding, structural adhesives, and automated composite manufacturing, are making this approach increasingly feasible.

Looking ahead, achieving truly sustainable lightweighting will require progress across the entire material lifecycle, from low-energy alloy production to improved recycling systems. Additionally, computational tools such as topology optimization will play an important role in designing structures that use materials more efficiently. Through continued innovation in materials and manufacturing, the automotive industry is well-positioned to deliver the next generation of electric vehicles that are lighter, safer, more efficient, and more environmentally responsible.

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Education, Labor Markets, and Economic Growth: A Descriptive Analysis of Smaller Economies and Their Trade Superpowers By Russell Qian

Abstract

Historically, developing countries like the Dominican Republic (DR) and the Democratic Republic of Congo (DRC) have maintained extensive trade relationships with global superpowers, but they continue to face persistent economic challenges. In this paper, I explore whether disparities in GDP between the DR and DRC, with respect to their superpower trade partners, affect the economic relationships and growth trajectories of these countries. I leverage longitudinal GDP data from 2000–2023, and compare the United States and China's trade, labor market, and educational attainment variables against their trade counterparts, DR and DRC's respective variables. My descriptive analysis revealed that high-income nations with universal secondary education translate trade into sustained wage increases and GDP growth. In contrast, developing exporters show rising exports but declining secondary-school completion, which in turn limits wage growth and constrains long-term economic potential. These findings suggest that trade alone does not create equitable economic growth in developing economies; rather, this paper points to the importance of investing in education and human capital.

Keywords

Developing countries, Superpower trade partners, Global Domestic Product (GDP), Education, Wages.

1 Introduction

1.1 Historical Context

Historically, the United States has displayed an interventionist approach to resolving foreign conflicts, meaning it is actively involved in other countries' affairs, usually through militaristic means, to promote its own goals or fulfill its agenda. This is evident from their military involvement during the Dominican Civil War, assisting in the elimination of dictator Rafael Trujillo, reflecting an imperialist "act first, then think" policy. This intervention extended U.S. economic influence, most notably in Dominican sugar production, which was dominated by American interests and marked by the exploitation of Black and Haitian labor.

Despite decades of trade relationships with their respective superpower trade partners, the Dominican Republic and the Democratic Republic of the Congo continue to face development challenges similar to those of a developing country. For example, between 2000 and 2023, the DRC's GDP per capita increased from approximately \$300 to \$600. In contrast, their major trading partner, China, increased their GDP per capita tenfold, from around \$953 to \$12,000 (World Bank, 2024). Theoretically, the DRC holds more promising potential GDP growth than China, with over \$2 trillion worth of key natural resources yet to be mined. Yet how does such a paradox—immense natural wealth coupled with persistent poverty—exist?

This paper explores whether differences in GDP between developing and developed nations are a key factor in economic relations, influencing the degree of independence, bargaining power, and general interactions. I built a time series dataset for pairs of countries, where each pair consists of a developing and a developed country, tracking how trade, investment, and aid ties with global superpowers have changed over the past two decades. Additionally, I plotted those shifts alongside their annual GDP growth. Finally, I created an integrated graph with the target developing and developed countries to determine whether their growth is inversely or directly related, helping me answer the question: do links to a superpower mean faster expansion, slower growth, or no obvious change?

There are numerous subtle economic interdependencies between developing and developed nations that shape their respective growth trajectories. However, sometimes, these interdependencies are particularly evident, for example, in the relationship between economic superpowers like the United States and China and developing countries like the Dominican Republic (DR) and the Democratic Republic of the Congo (DRC).

Since the US intervention in 1965, the DR has remained heavily reliant on the U.S., with exports to the U.S. valued at approximately \$7.5 billion and imports at \$10.4 billion. These export commodities include gold, silver, nickel, and cacao beans (OEC 2024). Furthermore, U.S. tourism constitutes around 31% of the Dominican tourism market, indicating a complex economic integration and dependency. The short-term implications of severing ties could mean considerable economic losses. However, long-term social and economic improvements could include potential reductions in racial discrimination and labor exploitation. This raises a central question: if the DR trades so extensively with the U.S., where are the economic benefits going? Why hasn't this translated into more sustainable development or self-sufficiency?

On the other side, China's involvement with developing nations exemplifies modern-day colonialism, prominently through its Belt and Road Initiative, a program that funds the construction of infrastructure to expand economic influence globally, particularly in Africa. China's investment in the DRC's mining sector, specifically in copper and cobalt extraction, comprises 41% of the DRC's exports to China. This has led to economic reliance similar to that of the DR's relationship with the U.S.

In both the DRC and DR, much of the revenue from exports fails to benefit the general population. In the DRC, profits from exported copper and cobalt are mostly absorbed by private mining companies or lost to government corruption. Similarly, in the DR, export income is absorbed by private firms with little to no tax from the government. Both cases result in funds never reaching their respective national treasuries, preventing proper reinvestment in public goods and infrastructure (Khoury, 2024).

It is imperative to understand the context of these four countries, as they will be the main cases analyzed in this paper. Their rich yet convoluted economic and political histories will serve as the foundation to discover who benefits from these relationships, how the resources and profits are distributed, and why economic growth in these nations has lagged. This paper seeks to

explain and quantify how these countries are economically growing and the direction of their trade relations, but also why they are growing the way they are.

1.2 Literature Review

Oliver E. Williamson's paper on transaction-cost economics (1979) provides foundational insights into the structural dynamics of economic interactions, a core foundation that is notably relevant to this research on the economic interdependence between developed and developing nations. Williamson argues that transaction costs—the expenses of enforcing contracts and ensuring exchanges—shape whether markets or hierarchical structures, such as firms, prevail. Given the facts about the DR and the DRC, it is crucial to understand these costs because they explain how multinational corporations and superpowers like the United States and China choose to organize their economic relations with developing countries. For example, the transactional cost framework can clarify why the U.S. maintains tight control over industries such as sugar in the DR, implementing a hierarchical control structure to minimize uncertainty and ensure profitability despite the social and economic costs. Williamson's theories provide essential context for analyzing how transaction structures contribute to sustained economic influence and interdependence between developed and developing economies.

Charles I. Jones's work on resource misallocation (2011) further supplements my analysis by highlighting how micro-level inefficiencies create a ripple effect through economies to generate macro-level disparities in wealth and productivity. This concept directly enriches my study of GDP variations between developed and developing countries. Jones utilizes an input-output economic framework to show that distortions in intermediate goods allocation significantly impede aggregate productivity and economic growth. Applied to my research, Jones's insights help illustrate how misallocations, such as exploitative labor practices in the DR's sugar industry or inefficient resource management in the DRC's mining sector, contribute to persistent economic disparities and dependence on economic superpowers. This theoretical perspective aids in providing reasoning for the detailed mechanisms behind GDP differences.

Acemoglu, Johnson, and Robinson's study on the rise of Europe (2005) argues that institutional quality, driven by decentralized control and distribution of trade profits, is necessary for sustained, continued economic growth. This finding aligns closely with my analysis of the DR and DRC's dependence on economic superpowers. In nations where institutional power remains centralized or controlled externally, such as through U.S. economic dominance in the DR or China's infrastructure and mining hold in the DRC, economic benefits are often unevenly distributed. However, institutional frameworks that encourage decentralized distribution and reinvestment can foster sustained growth and greater economic autonomy. My paper integrates these findings by exploring the institutional frameworks used to facilitate such change and the implications of economic dependence on superpowers. Specifically examining the degree to which centralized economic influence perpetuates wealth and social inequality.

Barry Eichengreen's analysis of the decline in U.S. basic industries (1988) identifies both domestic mismanagement and global economic pressures as critical factors that influence

industrial performance. The DR's and DRC's economic vulnerabilities become clearer once this perspective is applied to my research—both nations face intense pressures due to their reliance on exports to powerful trading partners. In addition, Eichengreen's conclusion that innovation and strategic adaptation, rather than protectionism, are critical for industrial sustainability creates a framework for my investigation into potential policy pathways for the DR and DRC. Specifically, his findings suggest potential strategies for these countries to mitigate the adverse impacts of economic dependency. One potential solution is embracing technological advancement and diversifying economic engagements. This framework is important for assessing the feasibility and outcomes of reducing dependency on their economic superpower partners. This, in turn, creates a more balanced and equitable economic relationship.

2 Methodology

2.1 Empirical Analysis

To map the relationships among wages, schooling, and trade, I followed a straightforward empirical workflow in Google Sheets. Annual data for 2000-2023 were first gathered from public sources (then deflated any monetary value to constant 2025 USD). Urban-wage averages serve as the best published substitute for middle-class earnings in China and the DRC, while national averages were available for the United States and the DR.

With the data cleaned and aligned by year, I built three sets of charts using Google Sheets' built-in graphing tools. Single-axis line charts (Figures 1- 5) trace wage growth within each country pair (US vs DR and China vs DRC). A second pair of line charts (Figure 6) tracks each nation's share of residents who finish secondary school, highlighting divergent human-capital paths. Finally, dual-axis charts (Figures 7-8) place trade flows on the left y-axis (billions of dollars) and education shares on the right y-axis (percent of population) to show whether growing imports in the United States and China, or expanding exports in the DR and DRC, move in step with changes in schooling. Conclusively, reading the figures together supplies the answer for my thesis: high-income importers with nearly universal secondary education translate trade into higher wages and consumption, while lower-income exporters grow by pulling teenagers out of school, limiting wage gains, which reinforces the global human-capital divide.

2.2 Data Collection

I would use data spanning 2000–2023, collected from reputable international and national sources. GDP figures were obtained from the International Monetary Fund (IMF), World Bank, Statista, and official government databases, with the values then converted to U.S dollars. Education data, specifically enrollment in primary and secondary schools, was collected from Statista and UNESCO. Lastly, the average wage rate of a middle-class worker and an urban class worker in the case of China came from CEIC data and respective national labor and statistical agencies. All monetary values were converted to USD using the most recent (2025) exchange

rates and adjusted for inflation to ensure consistency and comparability across countries. I use a single regression with interaction terms so we can directly see how education and wages correlate with GDP in both developed and developing countries. Wages stand in for consumer spending—when people earn more, they tend to spend more, boosting output—while education captures the long-term gains through improving skills and productivity, a factor in investments. I utilize the average salary of a middle-class worker and leave out minimum-wage effects because they do not have excess wealth to spend on excess consumption, and because GDP measurements do not fully reflect income inequality.

3 Results

For Figures 1–4, Real GDP represents GDP adjusted for inflation. C denotes household consumption expenditures on goods and services, while I captures gross private domestic investment in physical or capital assets such as factories, machinery, inventories, and residential construction, explicitly excluding financial-market purchases like stocks and bonds. G reflects government purchases of goods and services, but it does not include transfer payments such as Social Security benefits or other stipends. The US has had a steady and consistent increase in GDP over the past 23 years. Consumption was the largest component throughout, while investments, government spending, and exports grew moderately. However, US imports were significantly higher than its exports, leading to negative net exports. This trend did not change throughout the entire 23 years, highlighting the high reliance on foreign goods. In addition, note the 2008-2009 dip in overall GDP, which aligns with the global financial crisis during that time.

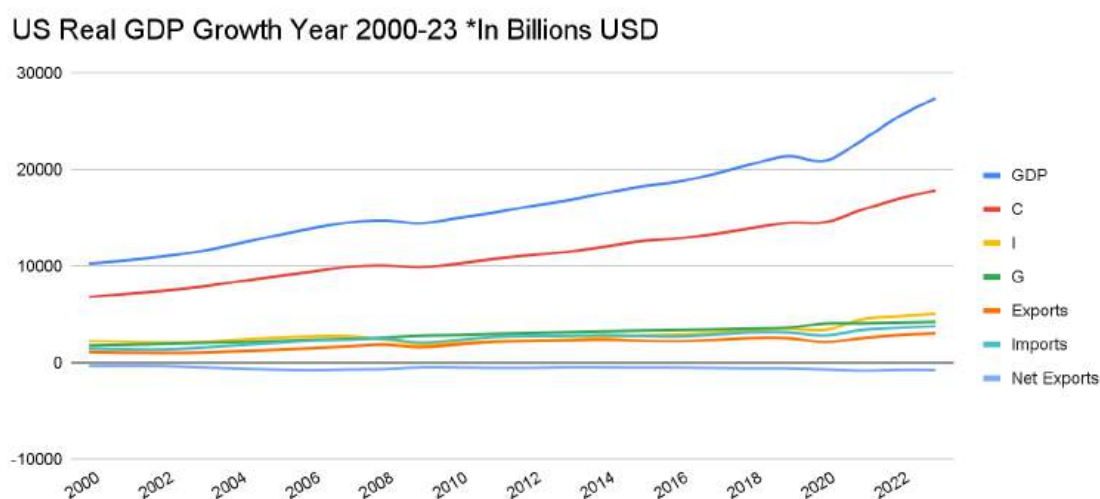


Figure 1. US Real GDP Growth Year 2000-2023. (World Bank World Development Indicators (WDI) and U.S. Bureau of Economic Analysis (BEA)) Annual real GDP and its expenditure components—household consumption (C), gross private domestic investment (I), general-government consumption (G), exports, and imports—are expressed in billions of constant 2025 U.S. dollars and deflated with the U.S. GDP-deflator series. Negative net exports ($NX = \text{exports} - \text{imports}$) appear as the gap between the export and import lines.

Figure 2 illustrates the gradual GDP growth of the DR, particularly accelerating after 2015. Consumption rises steadily, but investments and government spending generally remain low and inconsistent. This pattern potentially signals underlying governmental inefficiencies and limited economic diversification, though other factors may also be at play. Note the sharp increase in consumption, but a dip in overall GDP, which is due to the pandemic, as COVID-19 disrupted international trade and increased consumer demand for living necessities.

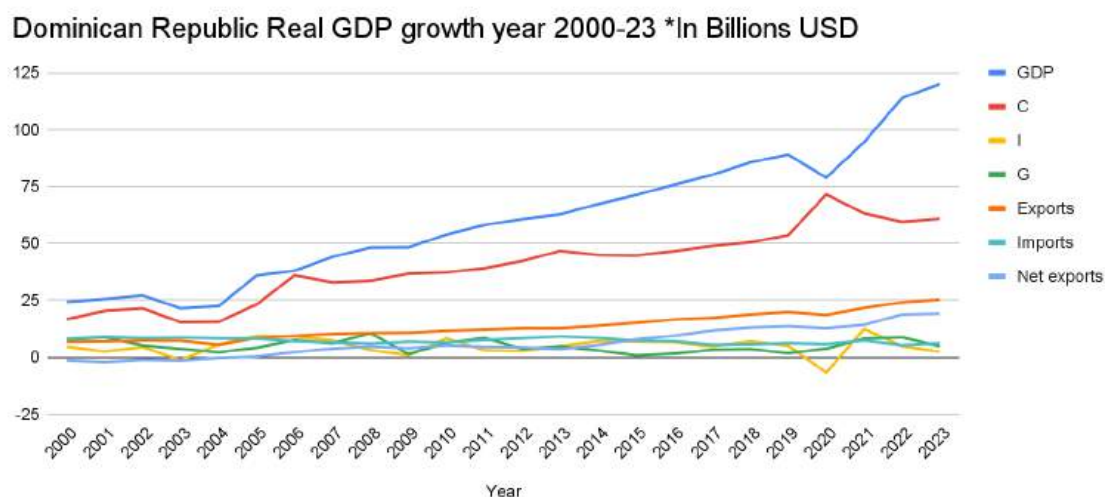


Figure 2. Dominican Republic Real GDP Growth Year 2000-2023. (International Monetary Fund (IMF) World Economic Outlook and Banco Central de la República Dominicana) Series definitions match Figure 1; values converted to constant 2025 U.S. dollars using the Dominican GDP deflator. Large year-to-year volatility in I and G reflects hurricane-related recovery and reconstruction spending and regular fiscal tightening.

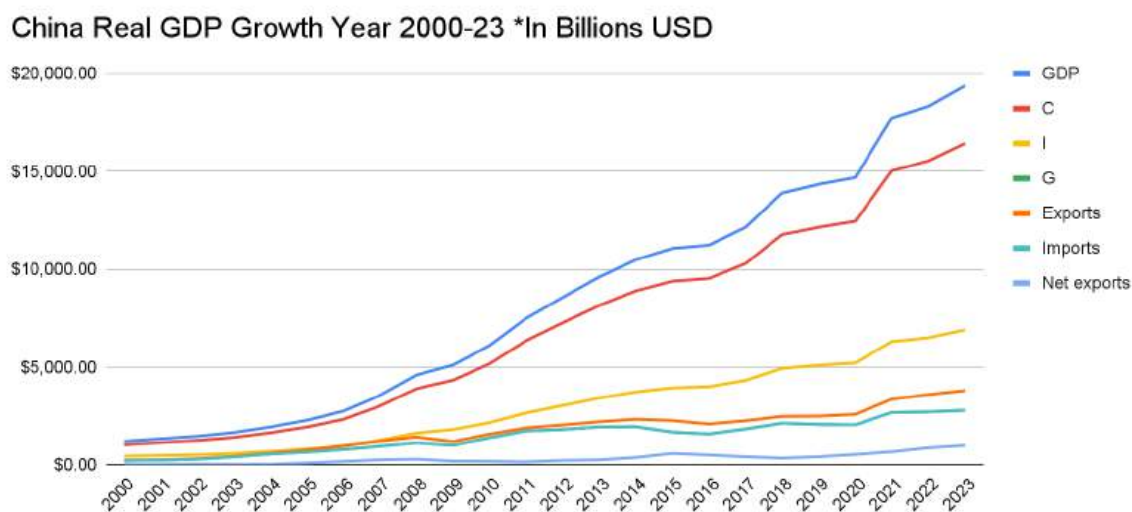


Figure 3. China Real GDP Growth Year 2000-2023. (National Bureau of Statistics of China and IMF WEO) Real series expressed in constant 2025 U.S. dollars via the Chinese GDP deflator and annual average exchange rates. Consumption includes household and nonprofit sectors.

Figure 3 illustrates the GDP growth of China. Overall, throughout the period 2000-2023, China's GDP rose relatively sharply compared to the U.S, with consumption being China's major contribution, in addition to its positive net export balance, which is due to the high demand for its workforce and its goods. The sudden increase in slope of the consumption graph is likely indicative of the population boom in the early 2010s due to the removal of the one-child policy. A stagnation in overall growth around 2020 indicates the impact of the COVID-19 pandemic. However, China's GDP growth quickly picks up momentum again, with investment growing to the steepest increase, signaling increased infrastructure and industrial expansion.

Figure 4 illustrates the GDP growth of the Democratic Republic of Congo. The DRC's GDP is on an increasing trend, but at a much lower scale compared to China. The sudden drop in GDP and investment in 2014 reflects the depreciation of the currency and its commodities as a result of increased government debt and internal government inefficiencies. Net exports remain positive, but the benefit is not reflected in domestic growth. This hints at potential foreign corporate dominance and corruption, which often leads to revenue leakage and embezzlement.

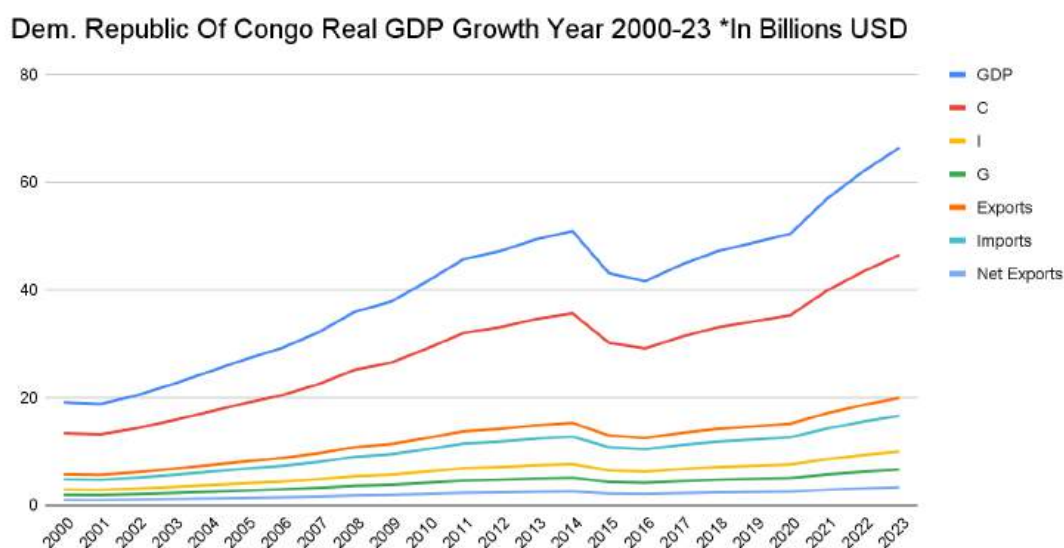
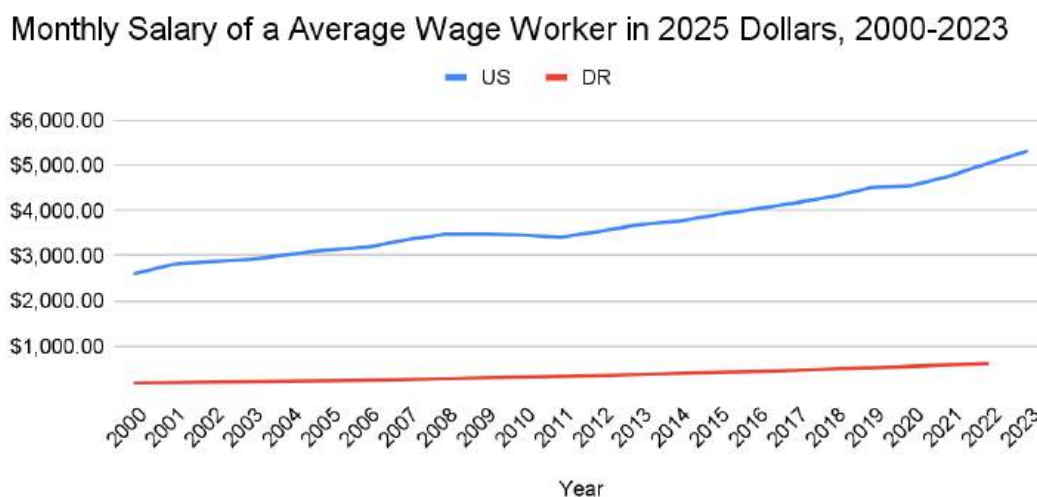


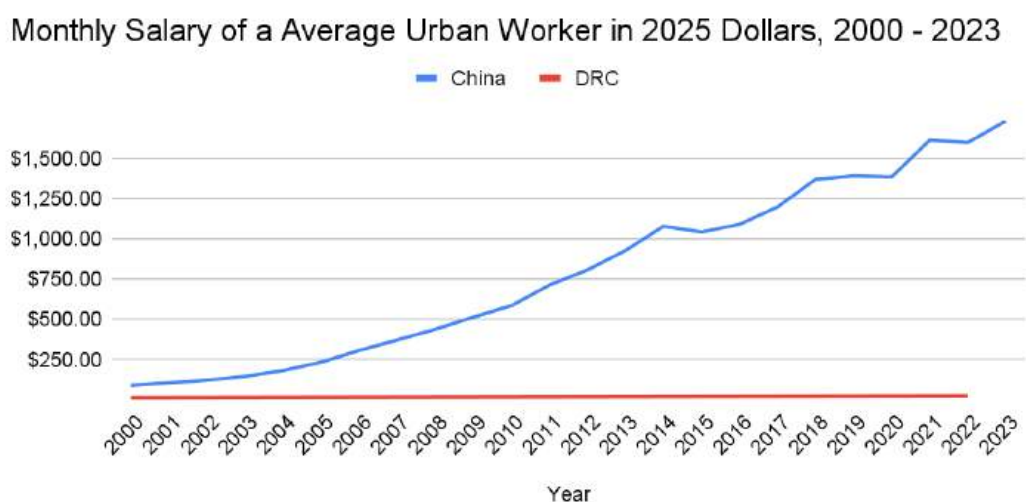
Figure 4. Dem. Republic Of Congo Real GDP Growth Year 2000-2023. (World Bank WDI and Banque Centrale du Congo) Constant-dollar conversion follows the DRC GDP deflator. Sharp declines in 2014–2015 mirror the 2014 franc depreciation and commodity-price shock.

Figure 5 depicts the average monthly wages from 2000-2023 across all four countries. Figure 5 illustrates that the average monthly salary for a U.S. middle-class worker starts at just under \$3,000 in 2000 and grows steadily until a minor dip during the late-2000s recession, then rises to nearly \$5,000 by 2023. Meanwhile, the monthly average wages of an urban Dominican worker increase from \$200 to \$700 across the same timeframe. Although growth does occur in both countries, there is a wide gap in the difference in the average wages. Figure 5(b) depicts a similar story for China and the DRC: Chinese average monthly wages of an urban worker rose after 2005 from \$250 and topping \$1,500 by 2023. On the other hand, the DRC trend line, which is upward sloping but with growth that is minute compared to that of China's, hugs the bottom

axis below \$100. For this comparison, I chart urban workers rather than the most optimal “middle-class” category because consistent, reliable data on middle-class workers is not currently available to the public in China or the DRC due to government-imposed restrictions on the publication of such data. Given that the great majority of working-class jobs are concentrated in the cities, urban pay is thus the best substitute for middle-class income.



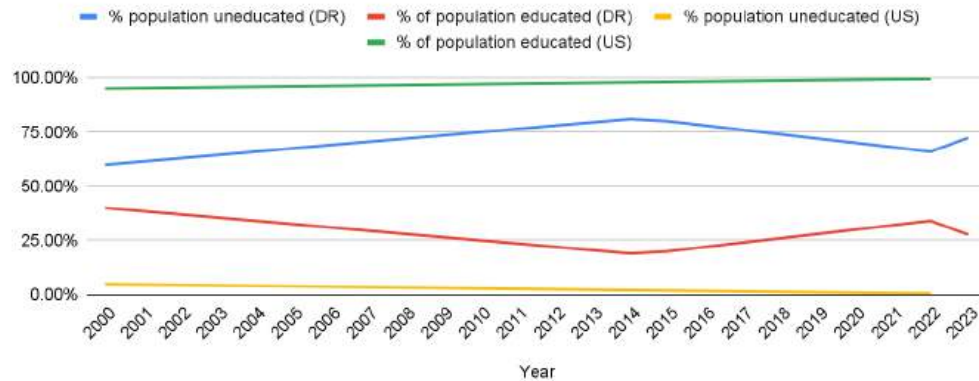
(a)



(b)

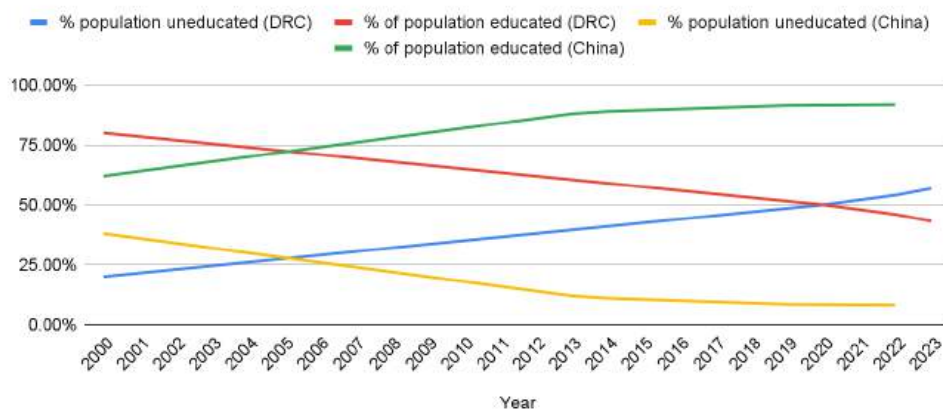
Figure 5. (a) Monthly Average Wage Worker in 2025 Dollars. (b) Monthly Salary of an Average Urban Worker in 2025 Dollars. (U.S. wages: Social Security Administration National Average Wage Index. Dominican wages: Ministerio de Trabajo; Statista. Chinese urban wages: CEIC Data/National Bureau of Statistics. DRC wages: ILOSTAT and national labour bulletins) All series are pretax averages for full-time employees; Chinese and DRC data cover urban workers (the best proxy for middle-class earnings because national coverage is unavailable due to middle-class earnings not being available for public view). Values are expressed in constant 2025 U.S. dollars using their respective country-specific CPI deflators.

% of Pop with Secondary Education, DR and U.S, 2000-2023



(a)

% of Pop with Secondary Education, DRC and China, 2000-2023



(b)

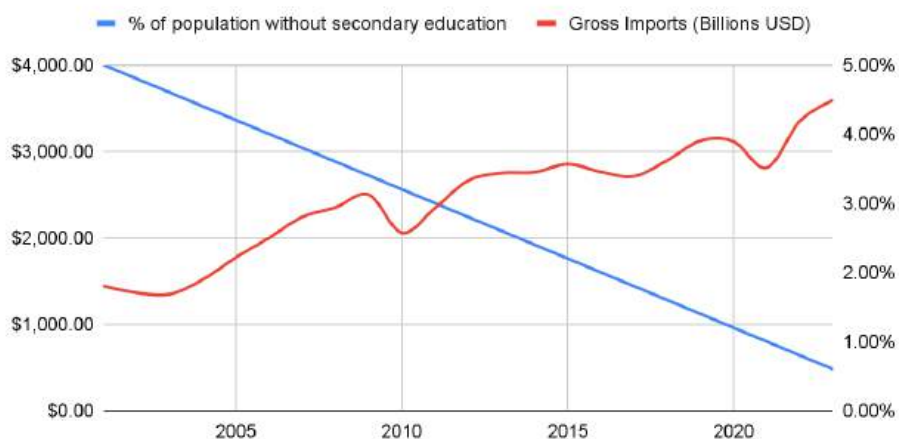
Figure 6. (a) Percent of population with secondary education, DR and U.S. (b) Percent of population with secondary education, DRC and China. (United States: IPUMS CPS; Statista. Dominican Republic: UNESCO UIS; Ministerio de Educación. China: UIS; National Bureau of Statistics yearbooks. DRC: UIS; national education surveys) The indicator measures the percentage of the population who have completed upper-secondary schooling.

Figure 6(a) shows secondary-school attainment during the period 2000-2023, with data extracted from Statista, IPUMS, and each country's respective governmental websites. There is a focus on secondary schooling because primary education is compulsory in all four countries, but secondary education is not. Figure 6(b) shows that the share of Dominicans who complete secondary education falls from roughly 40 percent in 2000 to about 20 percent by 2014, then climbs back towards 30 percent by 2023. In stark contrast, the U.S. line holds nearly consistently in the mid-90 percent range. This is mostly a result of secondary school being mandatory with a few religious exemptions, while secondary school is not mandatory in the DR. Figure 6(b) yields similar patterns for China and the DRC: China's educated percentage soared from 60 percent in 2000 to nearly 91 percent by 2023, while the DRC trends downward, from roughly 70 percent to

below 40 percent. This means that many teenagers leave school at that juncture to enter the labor force to meet the increased demand for labor in the production of labor-intensive products, such as natural resources, notably cobalt in the DRC. This distinction matters because the age at which young people leave school and enter the workforce directly relates to how much human capital investment a country is willing or able to make. Education is a major component of domestic capital and a direct driver of GDP. When students opt out of secondary schooling, there can be a loss of potential skills and productivity, which negatively impacts the economy and therefore GDP (UNESCO, 2024). In the sections that follow, I unpack the factors that drive certain teens to skip secondary education in the four targeted countries.

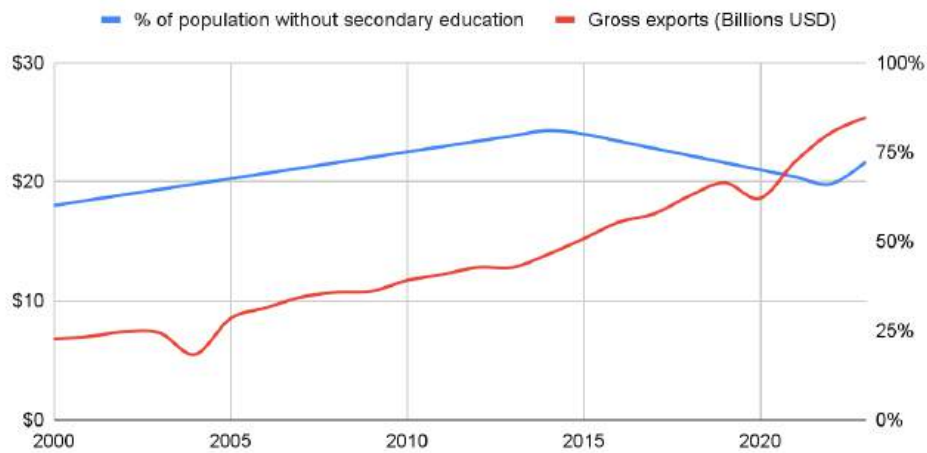
Figures 7 compare gross imports and exports with the percentage of the population without secondary education during the period 2000-2023. Imports are plotted for the United States because both countries are on the demand side of the trade relationship. Figure 7(b) shows that during the period 2000-2023, U.S. gross imports rose from roughly \$1 trillion to over \$3 trillion as the uneducated population decreased from about 4 percent to below 1 percent. It is the country purchasing goods from the Dominican Republic. Tracking U.S. import volumes allows me to ask whether a richer nation's growing demand for those exports has any quantifiable connection to education trends at home or its trading partners. Figure 7(b) pairs the DR across exports with the share of its population that completes secondary school. Exports surged from around \$5 billion to more than \$30 billion over the period 2000-2023. The education percentage faces a 20 percent initial decline, followed by a steady rally, then finally dipping over 5 percent. Here, I graph exports because the Dominican Republic is on the supply side of the equation. My goal is to find out whether rising export demand pulls teenagers out of school to meet labor needs, which negatively impacts the education rate.

Gross Imports and % Population Educated By Year (US), 2000-2023



(a)

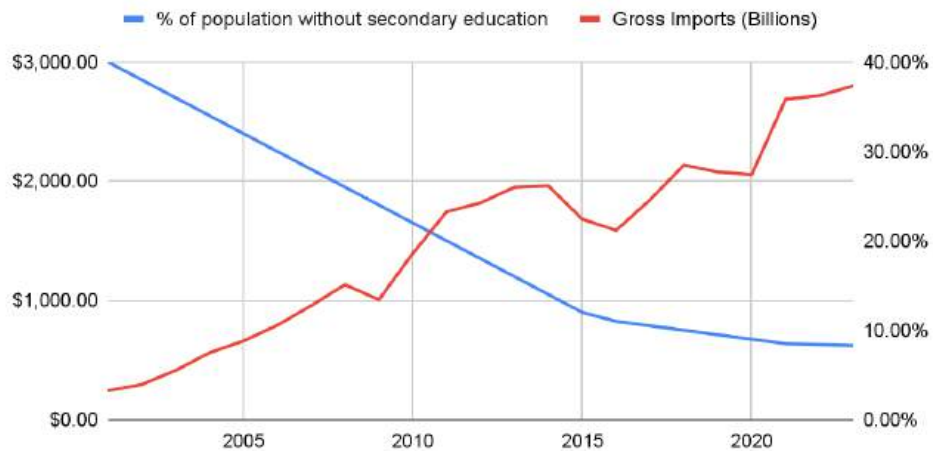
Gross Exports and % Population Educated By Year (DR), 2000-2023



(b)

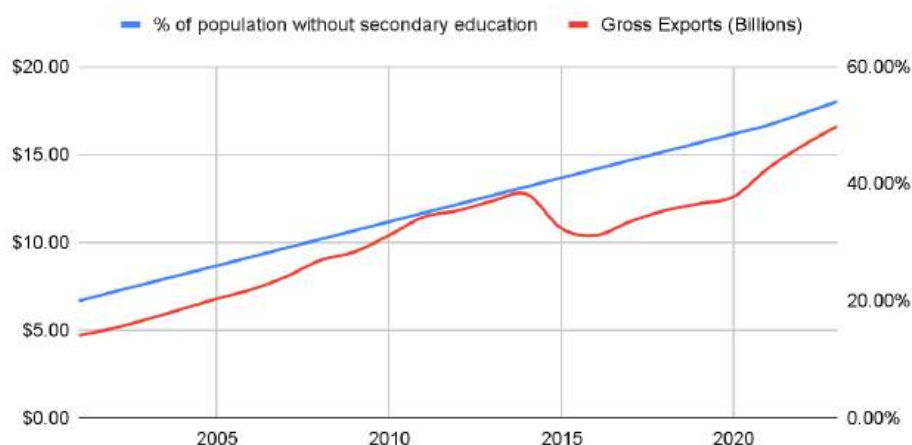
Figure 7. (a) Gross exports and percent population educated by year (U.S.). (b) Gross exports and percent population educated by year (DR). (Trade values from IMF Direction of Trade Statistics (imports) and World Bank WITS/OEC (exports); education series from Figure 6.) Monetary values are in billions of constant 2025 U.S. dollars. “Without secondary schooling” denotes the percentage of the population without a high school diploma.

Gross Imports and % Population Educated By Year (China), 2000-2023



(a)

Gross Exports and % Population Educated By Year (DRC), 2000-2023



(b)

Figure 8. (a) Gross exports and percent of the population educated by year (China). (b) Gross exports and percent of population educated by year (DRC). (Chinese import data: IMF DOTS. DRC export data: World Bank WITS; Banque Centrale du Congo. Education series from Figure 5.) Constant 2025 U.S. dollar conversion and education-gap definitions match Figure 6.

Lastly, Figure 8 extends the comparison to China and the DRC. Figure 8(a) shows China's imports rocketing from near zero in 2000 to roughly \$2.5 trillion by 2023, while the fraction without secondary schooling collapses from about 35 percent to roughly 7 percent. Figure 8(b) flips that script for the DRC: exports climb almost tenfold, peaking above \$15 billion, while the share of educated citizens falls by roughly 12 percent. To reiterate, concentrating on secondary education helps isolate the decision point where students either acquire additional skills or head straight into low-skill, resource-heavy sectors. Ultimately, this clarifies why soaring trade revenues in the DRC have not translated into growth in the share of the population acquiring post-secondary education.

4 Discussion

4.1 Analysis

Figure 5 confirms that real monthly wages rose in both the United States and the Dominican Republic (DR) between 2000 and 2023, yet the amount of growth diverged sharply: U.S. earnings climbed from roughly USD 3,000 to almost USD 5,000, while Dominican wages inch from about \$200 to only \$700. Figure 6(a) helps explain this gap. In the United States, secondary schooling is nearly universal—hovering around 99 percent throughout the period—so the country benefits from a consistently skilled labour force. Higher human-capital levels translate into greater worker productivity and higher average pay. Because household

consumption is the largest component of U.S. GDP, rising wages mean increased domestic demand. Figure 7(a) captures this effect: gross U.S. imports swell from about \$1 trillion to more than \$3 trillion as disposable incomes expand. The inverse relationship between the import curve and the tiny “uneducated” share of the population provides sufficient evidence that as education spreads, purchasing power and import demand grow in tandem.

The Dominican Republic presents the opposite dynamic. Figure 6(a) shows its secondary education rate going downward over much of the period, even as Figure 7(b) records an export boom from roughly \$5 billion to more than \$30 billion. The data suggest that export growth is being fuelled by labor-intensive, low-skill sectors (specifically raw-material extraction), which draw teenagers out of school to meet the foreign demand. Although export earnings rise, forgone schooling limits long-run productivity, and the gains are not reinvested in human capital. This pattern is consistent with concerns about weak fiscal governance in the sense that export revenues are generated, but they do not translate into broader educational attainment, which, by extension, means higher domestic consumption.

Figure 5b compares wage trajectories in China and the DRC. Chinese average monthly urban earnings increased from roughly \$250 a month in 2000 to about \$1,500 by 2023, whereas DRC wages remain below \$100 despite modest growth. We can find an explanation in Figure 6(b): China’s share of residents who complete secondary school rises by roughly twenty percentage points from 2000-2023, while the DRC’s educated share slips towards a 50-50 balance with the uneducated population. Similar to the U.S, China’s educational expansion means both wage growth and stronger domestic demand. Figure 8(a) shows imports surging from near zero to approximately \$2.5 trillion, mirroring the pattern in Figure 7(a) for the United States.

The DRC again follows the Dominican Republic’s path. Figure 8(b) indicates that exports expand almost tenfold, yet the proportion of educated citizens falls from about 20 percent to roughly 12 percent. Rising demand from industrial powers, notably China, appears to be met by drawing low-skill labor into resource extraction rather than by boosting educational investment. The result is a classic “resource-pull” effect: export revenues grow, but the domestic skill base stagnates, limiting the country’s capacity to climb the value chain and bottlenecking future wage growth.

Scoping out, the figures hint at an inherent institutional failure: sudden bursts in export revenue in the DR and the DRC are not being funneled into classrooms or laboratories. Even as export earnings surge, there is a flattening of wages and a decline in secondary-school completion, which suggests that current leaders let most profits stay in a few hands instead of investing them in education and skills for everyone. One way a regime, whether democratic or technocratic, can change this trajectory is by explicitly prioritizing the working and emerging middle classes by designating a fixed share of mining and manufacturing royalties for school construction and teacher pay, making upper-secondary education compulsory or genuinely free, and offering transparent tax credits for domestic research and development. These steps could turn unstable resource income into lasting skills, more innovation, and stronger economic

growth. While my graphs document the symptom—chronic underinvestment in education—I now see that a fuller explanation may lie in the architecture of governance itself. Therefore, future work and research on this topic could pair these trade and schooling trends with data on regime type, corruption scores, or major education-finance reforms to identify whether shifts in political institutions are the decisive lever for inclusive growth.

4.2 Future Work

Originally, this paper set out to tackle this question with a full ordinary least-squares regression that linked school enrollment rates and middle-class wages to GDP for each group of countries; however, the prerequisite coding and data demands were outside my current reach. I now turn to describe how I would empirically test my hypothesis via an econometric approach. I will describe the data I would use, the regression analysis I would implement, and will describe the key parameters in my regression analysis. This econometric approach would utilize a quantitative, time series regression analysis to examine the relationship between the economic engagement and influence by a global superpower (e.g, China and the United States) and the GDP growth of both a developed and a developing country. The objective is to determine if there is a correlation between economic interaction with a global superpower and changes in a nation's GDP.

The dependent variable in all regressions is the country's annual GDP. The first independent variable is the population enrolled in primary and secondary education. This represents human capital investment and access to foundational education. The second independent variable is the average annual wage rate, which reflects labor market conditions, income levels, and the likelihood of workers leaving the country for work. Together, these variables are used to estimate how workforce education and compensation contribute to the GDP variations across the developed and developing countries. Additionally, a dummy variable is included to distinguish between a developed country (coded as 0) and a developing country (coded as 1). This model allows for a direct comparison of how education and compensation influence GDP across the different developmental contexts.

A multiple linear regression model with interaction terms will be used to articulate the relationship between the independent and dependent variables across both countries. The model is specified as follows:

$$\text{GDP}_t = \beta_0 + \beta_1(\text{Education}_t) + \beta_2(\text{Wage}_t) + \beta_3(\text{CountryDummy}_t) + \beta_4(\text{Education}_t \times \text{CountryDummy}_t) + \beta_5(\text{Wage}_t \times \text{CountryDummy}_t) + \varepsilon_t$$

In this equation, GDP_t represents the gross domestic product in a certain year t . Education denotes the percentage of individuals enrolled in secondary education. Wage_t corresponds to the average annual wage of a middle-class worker. CountryDummy_t is a binary variable that indicates whether the country is developing (1 for the Dominican Republic and the Democratic Republic of the Congo) or developed (0 for the United States and China). The interaction terms

($\text{Education}_t \times \text{CountryDummy}_t$) and ($\text{Wage}_t \times \text{CountryDummy}_t$) allow for the comparison between two countries. The coefficients β_1 and β_2 estimate the marginal effects of educational attainment and wage level in developed countries, while β_3 , β_4 , and β_5 estimate the marginal effects in comparison to the developing countries. Lastly, β_0 is the intercept, and ε_T is the error term.

The estimated coefficients were interpreted to determine the strength and direction of the relationships. A positive and statistically significant coefficient for educational attainment would indicate that broader access and attendance in primary and secondary education are associated with increased GDP. Similarly, a positive coefficient for wage rate would suggest that rising wages contribute to greater economic output. The interactions between coefficients β_4 and β_5 measure how the effects of education and wages differ in developing countries compared to developed countries. If these differences are statistically significant, it means that the influence of human capital (e.g., education) and compensation on GDP is fundamentally different in the developing country. Further evidence and reasoning beyond statistical data would be needed to provide support for the results. The dummy coefficient β_3 represents the baseline GDP gap between the two countries in comparison. I am most interested in the education parameters (β_1 and β_4) because education is a key factor for human capital growth (investments) and GDP growth. In developed countries ($\text{CountryDummy} = 0$), every one-percentage point increase in secondary-school completion equates to a β_1 -unit rise in GDP, with the assumption that wages stay the same. The interaction term β_4 shows how that effect changes in developing nations ($\text{CountryDummy} = 1$): a positive β_4 means each additional percentage point of educated adults delivers an even bigger GDP boost there. At its core, focusing on β_1 and β_4 is about recognizing that education builds the skills and knowledge that power economic growth and increase the potential possibilities curve (GDP). As more people finish secondary school, they learn to use new technologies, solve problems creatively, and work more efficiently, which ultimately raises output per worker.

5 Conclusion

This paper set out to test a simple yet profound hypothesis: the size of a nation's GDP will determine, at large, who can capture the most gains from trade. This is because richer importers are better positioned to translate global commerce into higher wages and increased domestic investments (human and physical capital), whereas poorer exporters often cannot. The evidence points to a clear answer: education is the decisive factor. In the United States and China, near-universal secondary schooling supports productivity, lifts wages, and creates a positive feedback loop of rising consumption and import demand. In stark contrast, in the Dominican Republic and the DRC, low and oftentimes falling secondary completion rates leave workers in low-skill jobs, even when export revenue increases. Combined with other factors in play, such as weak governmental institutions, leakage of funds due to internal corruption, and "brain drain" as the best-qualified workers emigrate, these market failures stall GDP growth even in the presence of a positive net export.

These findings then open several avenues for extension. A larger cross-country panel would test whether the trade–education relationship holds more broadly, improving external validity. Future work could ask: *to what extent does trade itself depress schooling in exporter economies? How does education reshape the sectoral mix of labor markets in importing versus exporting countries?* These questions can be addressed through a macroeconomics lens, such as Lorenz-curve decompositions to track shifts in income inequality, Phillips-curve analysis to link wage dynamics with unemployment, and mapping trade shocks onto movements of the long-run aggregate supply (LRAS) curve to gauge potential output.

In addition, it is also clear that there exist limitations within this study. It covers only four countries and relies on urban wages as a proxy for middle-class income in two of them. Also, it is descriptive rather than causal, on top of the fact that secondary-completion rates do not capture education quality. Nonetheless, the core takeaway is present: trade by itself won't deliver lasting, broad-based growth unless part of the export profits is channeled into education. Developing countries should reassess whether current trade relationships truly serve their long-term interests. In some cases, reducing or even severing these ties could be beneficial. While such a move would cause short-term negative effects to its economy, it could free up resources to reinvest at home and prioritize education rather than simply meeting the demands of foreign markets.

6 Acknowledgements

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Hope in the Mailbag: How Letters Helped Win the War By Brayden Choe

Introduction

The emotional and psychological strain of WWII extended far beyond the battlefield in which war played a significant role in dividing families and loved ones. For young American servicemen, the distance from home was not just measured in miles, but in silence. The US military recognized the need to take control of the morale and turn it into a weapon to bolster US servicemen's mental perseverance. General Dwight D. Eisenhower rightly knew that the morale of soldiers directly correlated with their ability to fight in a war ("Quotes by Eisenhower" 4). Eisenhower saw the importance of sustaining hope among his men as essential to keeping the men strong despite the pressures of combat. In Eisenhower's view, these measures were an integral part of the US war machine. By providing quick communication with loved ones, the US had the advantage to reassure American soldiers that their lives at home could stay intact with these letters.

Today, technological innovations gave our society video calls and instant messages that have become essential lifelines to connect us to those we care about. But in the 1940s, only advances in V-Mail, a hybrid of microfilming letters to reduce the gross weight of packages, and post service that expedited military mail were available. Compared to previous archaic methods of letter transport, the quicker communication method allowed soldiers to communicate with loved ones within days apart. When US forces were mobilized overseas, the Army and Navy established separate Army Post Offices and Fleet Post Offices that worked on top of the US postal system. Letters were light in comparison to care parcels, and the reduction of letter weight solved a part of the delays caused by logistics. To Eisenhower, morale correlated with strengthening mental endurance for his men. He issued not only orders for logistics and weapons but also he circulated letters, news, and bulletins. Soldiers who were cut off from civilization struggled to maintain their convictions while soldiers who received letters from loved ones showed more resilience under pressure (Greenbaum 1). Even the post office prioritized military communications first over any domestic transmissions.

History

The Army Postal Service expanded dramatically to meet the demand by delivering billions of letters each year across borders. This was only made possible by the reduction in the weight of the letters in addition to the more efficient processing of the letters to the correct destination. These letters became sacred: offering more than updates, they were proof of life, love, and memory for many soldiers. The US Library of Congress recognized their cultural and historical value and preserved many of the soldiers' letters. Research programs such as the Veterans History Project depicted the raw emotions captured in a soldier's handwriting. The letters provided historians with a rare glimpse of how the emotional struggle matched with the timeline of the war effort.

One of the longest documented letter exchanges came from a soldier named Bobby Stone. For Bobby, a young bombardier trainee stationed in a small town of Childress, TX, mail was the only source of comfort against the monotony and isolation of military life. Because of Bobby's vivid description of military life, the rich collection provided evidence of any emotional stress and changes caused by significant events throughout the war. He described the base as dusty, flat, and painfully dull. "Mail is especially welcome," he said, emphasizing the loneliness that gnawed at him each day. Recognizing the emotional stakes of war, the US military actively created systems like V-Mail to deliver letters quickly and securely.

The US military showed that communication was not just personal: it was indoctrinated by the Information and Education Division of the US military. During World War II, personal letters and wartime mailing innovations like V-Mail were essential to sustaining morale among US soldiers and civilians while also highlighting the US military's strategic use of communication as a psychological weapon to win both the war and the will to overcome the enemy.

Literary Review

Historians Judy Litoff and David Smith, writers of "Fighting Fascism in Europe," researched and edited the letters of Lawrence Cane, who was a US soldier in the 238th Engineer Combat Battalion. Litoff and Smith took the letters and infused contextual evidence that reflected the importance of a soldier's need to endure and survive through such harrowing warfare. By understanding the personal experience of Lawrence Cane throughout World War II, we see a pattern that closely parallels the writings of Bobby Stone, the young soldier from Childress. Despite their separation by geography and their own assignment, both of the soldiers shared the same form of psychological survival. These correspondences between Bobby's and Cane's reflections were not coincidental. The voice of the soldiers was shaped by the hybrid postal system enforced by the prevalent military policies. Their personal accounts converge into a central theme of how the US military viewed the importance of correspondence letters between family members.

Primary Evidence and Methodology

Still currently under review, Bobby Stone's letters were still under review and analyzed through the Gilder Lehrman Institute of American History. The sheer volume of constant communication between Stone and his family made the research possible to track the nuances and changes that occurred throughout the war period. The letters from Bobby offered a vivid lens into base camp life in the 1940s, revealing the emotional and environmental conditions faced by soldiers in training. From 1942 to 1945, Bobby sent over 150 letters, postcards, and telegrams that chronicled his letters from enlistment to his final service assignment. His words were not just observations as he included words that described his emotional status. They described what it meant to be young, far from home, and swallowed by military routine. The current research into translating and contextualizing the meaning within the letters continue to shape the

understanding of significant events that happened during training and military warfare. The gambit of experiences from his training in the barracks to his time doing military exercises helped to define the transitional periods of his morale. As Bobby described barrack life, his descriptions were stark, Childress was a “flat, dusty”⁴¹ town with poor food and little to distract the mind. “Please write often. It’s really lonely out here, and I do mean lonely,”⁴² Bobby pleaded, giving a glimpse to a psychological burden that often began before soldiers ever saw combat (Stone, June 27, 1943). The repetitiveness of training combined with geographic and emotional isolation created a desperate need for human connection, and for Bobby, mail became the only source of comfort. He ended another letter with, “No more, except let’s hear from you ‘cause mail is really welcomed way out here”⁴³ (Stone, Dec. 16, 1943). These instances revealed how deeply letters served as an emotional plea, a lifeline to life back home for Bobby. The letters served as an ideal candidate for review and comparison to build evidence for an intentional system by the US military to boost morale. By researching the Bobby Stone collection, more evidence emerges for how personal letters revealed not only individual emotional struggles but also a larger system of morale management. This literary review utilizes qualitative content analysis of Stone’s 150+ letters, telegrams, and postcards about his account of WWII. The methodology reveals how language, repetition, and emotional appeal for mail reveal patterns of this psychological parallelism.

Analysis

From 1942 - 1944, Stone wrote to his family members Mildred and Eddie that echoed a sense of emotional dependency, saying, “Again many thanks for all your thoughtfulness Mildred, you know how I appreciate that,” while confessing that “life isn’t very fun”⁴⁴ (Stone, Mar. 5, 1944). These simple words illustrated how letters were not just informative, but they were restorative for these American servicemen by giving them the strength to endure each day. By tracking the number of appreciative sentences and phrases, the letters reveal Stone’s desire to reconnect with family on a weekly basis. Stone described his surprise by the speed of sending letters by V-mail, “Guess it was one of the speediest letters I’ve ever sent you” (Stone, Feb 22, 1945). The seamless ability to even know the daily lives and the occurrences in Stone’s family life helped to maintain his morale to stay in the war effort. In another instance, Stone expresses his humor when he surprised his family with a rare phone call in writing, “I’m so glad that you got such a kick out of my two phone calls” (Stone, Mar 2, 1945). Again, the transcribed letter revealed Stone’s need to convey his need to connect with his loved ones. Despite the challenges

⁴¹ Stone, Robert. “To Jacob Stone, Beatrice Stone, Don Stone, and Jim Stone.” Received by Jacob Stone, Beatrice Stone, Don Stone, Jim Stone, 27 June 1943

⁴² Stone, Robert. “To Jacob Stone, Beatrice Stone, Don Stone, and Jim Stone.” Received by Jacob Stone, Beatrice Stone, Don Stone, Jim Stone, 27 June 1943

⁴³ Stone, Robert. “To Jacob Stone and Beatrice Stone.” Received by Jacob Stone, Beatrice Stone, 16 Dec. 1943

⁴⁴ Stone, Robert. “To Mildred Hilson and Edwin Hilson.” Received by Midred and Eddie, 5 Mar. 1944

of fighting in a war, the most difficult time of war happened when soldiers lose that important support from loved ones. Stone explained even his reliance on receiving mail by exclaiming,

“Everything is happening very fast and the old U.S. is getting in a few good licks after a long period of just holding their own. I'm so glad that you got such a kick out of my two phone calls” (Stone, 22 , Feb. 1945). The affirmation described by Stone confirmed that Stone relied on the steady transmission of letters to keep his sanity. The repeated expression of thankfulness to receive each letter persisted throughout his station throughout the war.

Historian Susan Montgomerie explained that letters “were a conduit for the exchange of information and a way of keeping relationships going during periods of extended separation”⁴⁵ (Dietrich 25). In other words, they preserved not just morale but also mental stability from quick communicable letters. In an annual report by the US Postmaster General, the significance of quick mail revealed huge advantages as the “...frequent and rapid communication with parents, associates, and other loved ones strengthens fortitude, enlivens patriotism, makes loneliness endurable, and inspires to even greater devotion the men and women who are carrying on our fight” (National WWII Museum). This belief turned into policy: mail delivery transformed from a service to a strategic priority. Letters offered what no uniform or rank could: an emotional pill that satiated a soldier’s mental health.

Frank, a soldier whose letters to his wife Sally were preserved in the book *Army GI, Pacifist Go* put it plainly, “Every single word is a morsel of courage for me”⁴⁶ (Dietrich 25). In the mundane of wartime life, his wife’s letters did more than inform by nourishing his emotional survival. Each word became a tangible form, a reason to persevere through fear, boredom, and uncertainty. Frank’s statement reinforced that morale was not maintained solely through rations, routines, or military discipline, but through emotional connection. His language, words like “morsel”, evoked a hunger to feed his mind more than his body. This emotional insight was no accident, since Army Chief of Staff General George C. Marshall created a Morale Branch, later renamed the Information and Education Division, under Brigadier General Frederick H. Osborn to keep soldiers mentally fit. The division’s mission stressed that reliable news, recreation, and mail were as critical to combat readiness as rifles and rations. Its first mandate was to safeguard steady mail delivery. The War Department made that a high priority in Pamphlet No. 21-1, describing V-Mail as “an expeditious mail program which provides for quick mail service to and from soldiers overseas.”⁴⁷ By framing speedier correspondence as a matter of readiness, Marshall and Osborn turned mail into a necessary instrument for the US.

⁴⁵ Dietrich, Frank, et al. *Army GI, Pacifist Co: The World War II Letters of Frank Dietrich and Albert Dietrich*. Fordham University Press, 2022.

⁴⁶ Dietrich, Frank, et al. *Army GI, Pacifist Co: The World War II Letters of Frank Dietrich and Albert Dietrich*. Fordham University Press, 2022.

⁴⁷ Military , US. *Pamphlet No.21-1*

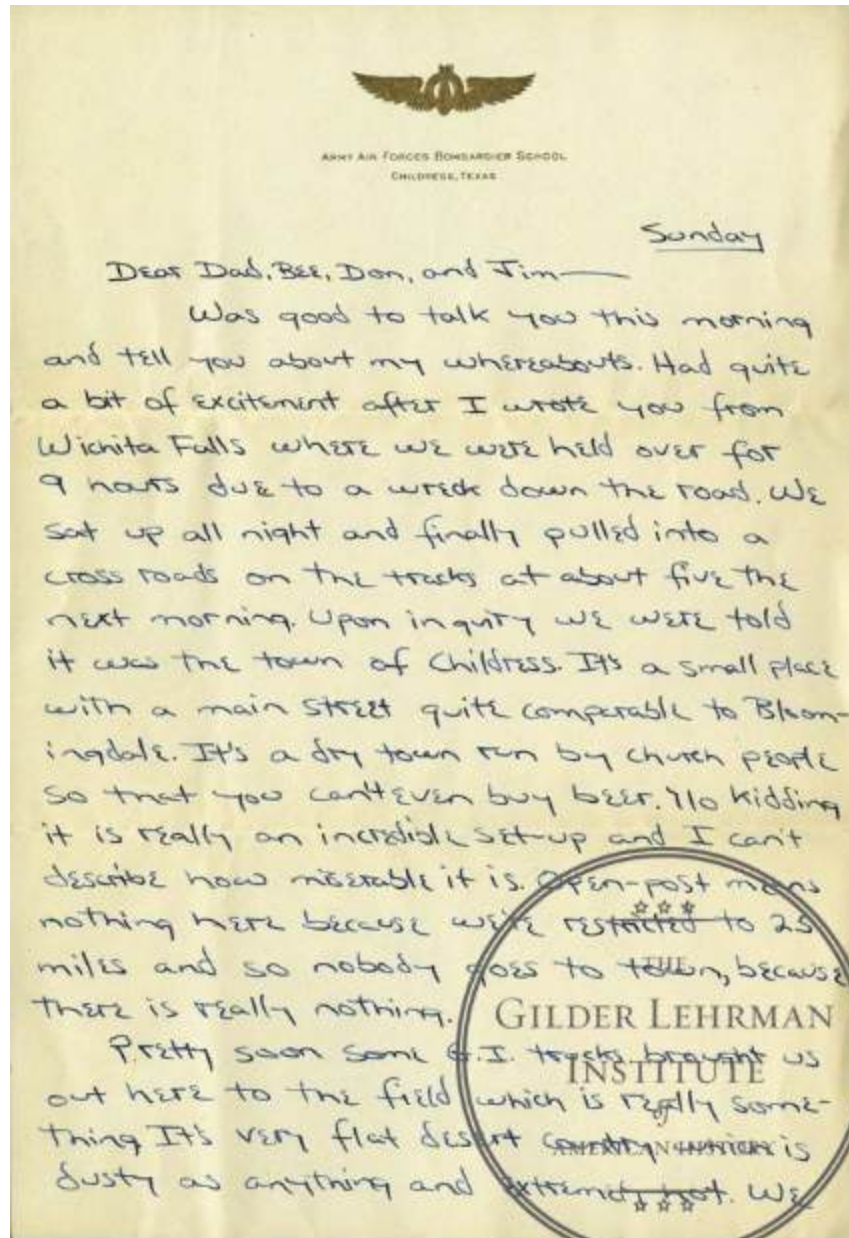
Letters were never mere handwritten messages on paper in World War II. They were strategic lifelines that calmed anxieties and fortified the will to fight. From Bobby's barracks in Childress to Frank's cramped bunk on a transport ship, the written word transformed isolation into connections and monotony into meaning. The US military recognized this power and institutionalized it through an expansive postal network and invention of V-Mail. By treating communication with the same urgency as ammunition and rations, they weaponized empathy by proving that victory depended on both material resources and emotional endurance. Seventy five years later, our era of instant messages and video calls may seem worlds apart from microfilmed letters and censored envelopes, yet the lesson persists: the human spirit still requires the tangible reminders of loved ones. World War II's postal innovation, born out of necessity and shaped by military strategy, underscores a simple truth: wars are, indeed, won in hearts and minds before the outcome of battles. The United States correctly fought not just for territory but for the morale that made ultimate victory possible.

Conclusion

From Bobby Stone's descriptions of loneliness in Childress to Lawrence Cane's reflections from the European front, each letter reveals a shared pattern of psychological resilience. The words and voices of these individuals tell the simple truth that the US military understood the importance of morale as a weapon. By institutionalizing a speedy system within the Army Postal Service and V-mail, the US established faster communications that delivered letters with the same urgency as ammunition or food rations.

What makes these soldiers' letters so significant is not only their personal value but also their use to maintain order and morale. As Eisenhower and Marshall revealed, the spirit of a soldier could not be satiated just by the amount of weapons or resources alone. There is a very real importance on the nourishment from human connection in the form of letters from family members. The legacy of wartime letters exists in our own timeline through instant messaging and video calls. Even though the platform and technology has changed, the lesson remains unchanged. Technology shapes how we communicate and the speed of which we make a human connection. The victory of World War II was not just battle wins but also the resilience the soldiers had during the fights.

Appendix



A letter from a Trainee, Robert "Bobby" Stone, at Childress Army Airfield, TX, 1944. (1 of 4)⁴⁸

WWII

⁴⁸Stone, Robert. "To Jacob Stone, Beatrice Stone, Don Stone, and Jim Stone." Received by Jacob Stone, Beatrice Stone, Don Stone, Jim Stone, 27 June 1943.

live in single story barracks that aren't too hot. The food isn't ~~comparable~~ to Ellington but it's not bad. About the only good thing so far is the fellows. We have a class of about 120 and there're really great guys.

Starting with our class the course has been changed from 12 to 18 long weeks. We will graduate as "Bombagators" (Bombardier-Navigators). In fact, the first thing we take up is navigation which is meant to be mighty rough. The upper class says that the work here is really tough and washouts are frequent. All our officers have told us the courses and flying are incomparable to anything we've ever done before. Incidentally our C.O. is a Captain who's hard as nails and known to be a stickler. The discipline here is very strict since they turn out ^{good} officers as well as bombardiers.

Our course is so tough and keeps us so busy that we never have a minute to our self. This time I really mean it ^{***} when I say you won't hear from me because I know we'll have no free time. ~~GRUBER LERMAN~~ appreciate it if you'd tell all my friends that I'll really appreciate mail but won't be able to write back, as much as I'd like to. Please ask everyone to write because it's ^{***} really lonely.

A letter from a WWII Trainee, Robert "Bobby" Stone, at Childress Army Airfield, TX, 1944. (2 of 4)⁴⁹

⁴⁹Stone, Robert. "To Jacob Stone, Beatrice Stone, Don Stone, and Jim Stone." Received by Jacob Stone, Beatrice Stone, Don Stone, Jim Stone, 27 June 1943.

and mail will be especially welcomed. I hate to lose contact with everyone but writing will be an impossibility from all indications.

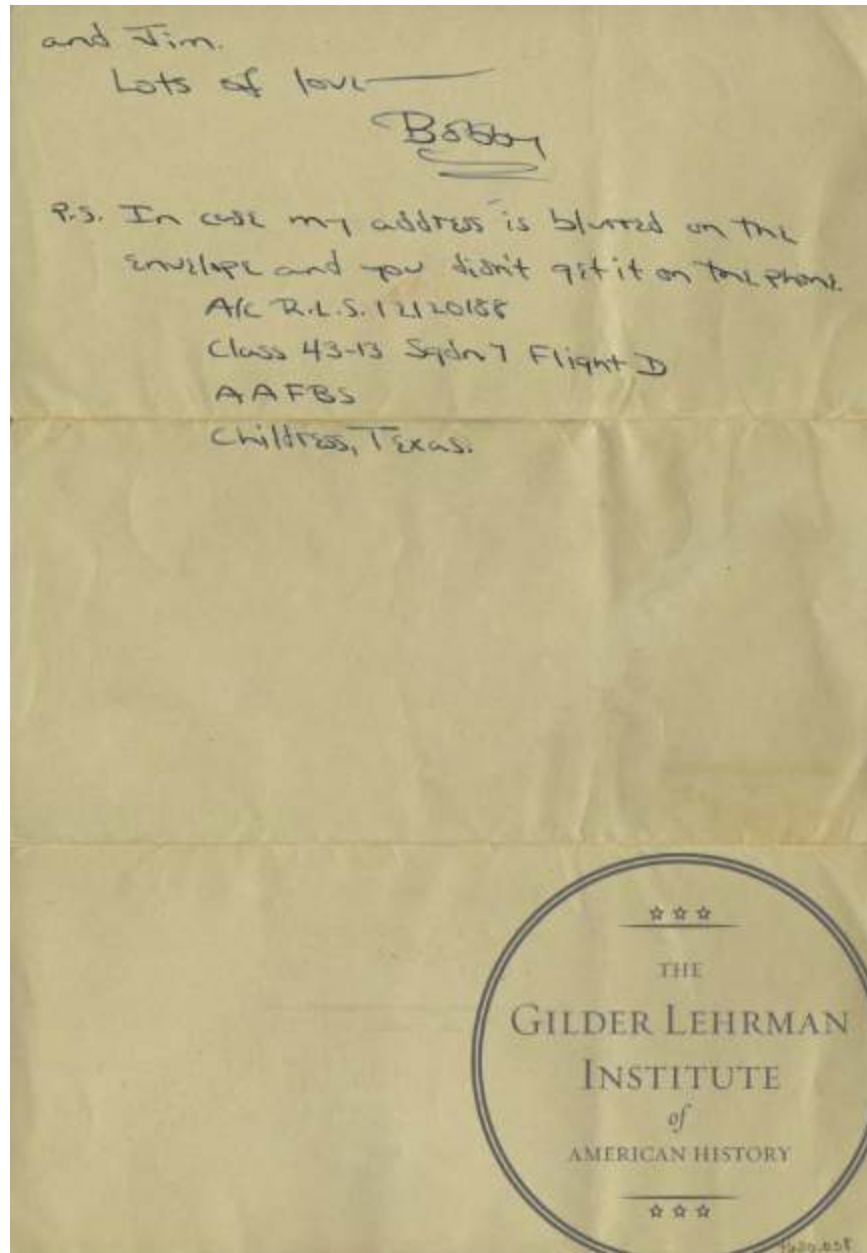
The day we arrived we were issued a lot of new equipment. Each man got a weather wrist watch, a stop watch, a series of complicated computers and dials, bombing tables, a lawyer's brief case, rulers and compasses, a drawing board, lots of tech manuals, and a box of books and small gadgets none of which mean anything to us. It was just like Xmas opening box after box of instruments etc.

Just had a thought. One of the boys has a camera here, most illegal of course. We thought we'd take some snaps and send them home but unfortunately we can't get film. If you could get us some "XX 828" Kodak film I'd really appreciate it. If you can send some, wrap it in a box that has nothing to do with photography because we'd be in a real mess if detected.

Guess I've told you just about everything that's happened so far. I hope you'll understand the setup here because it's ^{THE} ~~WILDER~~ ^{LEHRMAN} ~~WILDER~~ ^{LEHRMAN} and getting through will be a real ~~hard~~ ^{hard} ~~thing~~ ^{thing}. Please write often because it's really lonely out here and I do miss home. Be sure to send any letters I write you ~~to~~ ^{to} Don.

A letter from a WWII Trainee, Robert "Bobby" Stone, at Childress Army Airfield, TX, 1944. (3 of 4)⁵⁰

⁵⁰Stone, Robert. "To Jacob Stone, Beatrice Stone, Don Stone, and Jim Stone." Received by Jacob Stone, Beatrice Stone, Don Stone, Jim Stone, 27 June 1943.



A letter from a WWII Trainee, Robert “Bobby” Stone, at Childress Army Airfield, TX, 1944. (4 of 4)⁵¹

⁵¹Stone, Robert. “To Jacob Stone, Beatrice Stone, Don Stone, and Jim Stone.” Received by Jacob Stone, Beatrice Stone, Don Stone, Jim Stone, 27 June 1943.

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A Comparative Analysis of Methods of Feral Pigeon Control and Cross-Environmental Applications By Derek Hsi

Background

The feral pigeon (*Columba livia*) is a highly invasive pest bird causing significant economic and health impacts. To combat these birds, various methods have been deployed, but their efficacy is highly variable.

Objective

This study performs a comparative analysis of methods of feral pigeon control, and examines strategies that may be applicable across urban and rural areas.

Methods

Pigeon control methods were divided into seven categories: physical deterrence, chemical deterrence, exclusion, habitat modification, lethal control, non-lethal control, and multidisciplinary approaches. Thirty-two studies, encompassing forty-one trials, were gathered from a literature search and a percent effectiveness value was obtained by calculating the change in pigeon populations in the target area over the study period. In addition, factors such as environment, scalability, cost, ethics, and long-term sustainability were also considered.

Results

Chemical and exclusion deterrents produced 95% and 87% population reductions respectively, but were difficult to scale over larger areas. Multidisciplinary approaches produced 66% reductions, although varied depending on the environment studied. Habitat modification and nonlethal control methods produced 50% and 46% population reductions, but were expensive to implement. Lethal control produced 56% population reduction, but carried ethical concerns as well as long-term sustainability concerns. Physical deterrents were the least effective, primarily due to habituation, only producing 17% population reduction.

Conclusions

While chemical and exclusion deterrents were most effective, consideration should also be given to factors such as environment, scalability, cost, ethics, and long-term sustainability. Future directions of study include implementation of emerging technologies such as drones, lasers, and AI applications.

1) Introduction

The feral pigeon is a domestic offshoot of the wild rock dove, *Columba livia*. Feral pigeons possess several traits that make them a particularly invasive species in and around urban areas. While wild rock dove populations are known to nest on cliffs and rock ledges, their feral counterparts have adapted to nesting on ledges of buildings. Pigeon population density generally

increases closer to city centers and near anthropogenic food sources. Pigeons also have a high reproductive capacity. They have a 3-5-year lifespan, and breeding pairs can have 5-6 broods of 1-3 eggs annually (Johnston & Janiga 1995). Pigeons also exhibit significant adaptive capacity, demonstrating learning and innovative behaviors in response to environmental stimuli. For example, pigeons exposed to a novel object next to a food source initially demonstrated a reluctance to eat the food, but their hesitancy dropped after repeated exposure to the object (Bouchard et al. 2007). Although feral pigeons thrive in urban environments, they can also damage crops in agricultural areas. They have been known to travel up to 20 kilometers per day when foraging, allowing the same population of birds to affect multiple environments at the same time (Elleva et al. 1975).

1.1) Species Impacts

Feral pigeons have a variety of negative impacts on human society, including health issues, nuisance, and degradation of infrastructure. They serve as a significant reservoir for multiple viral, bacterial, and fungal diseases. Ninety-nine percent of transmissions to humans occur through aerosolized pigeon feces, and immunocompromised individuals are especially at risk (Haag-Wackernagel & Moch 2004). Additionally, pigeon droppings are an eyesore that can foul windowsills, rooftops, and sidewalks, leading to additional costs for building owners and local communities, estimated at hundreds of millions of dollars annually in the United States alone (Pimentel et al. 2000). Droppings may be acidic, so they can corrode building materials, including copper and steel (Shrestha et al. 2022, Felder 2007). Pigeons are significant agricultural pests as well. Though crop losses to feral pigeons worldwide are small, pigeons may inflict significant damage on local areas (Cotuna et al. 2025; Lawson 1979). These negative effects have forced both city officials and farmers to adopt a variety of methods and strategies to control pigeon populations.

1.2) Literature Review

Numerous studies and reviews have been published on bird control. Klug et al. (2023) summarized control methods for various invasive birds, dividing them into urban and agricultural environments. They also separated studies by the bird species. Their findings indicate that a large amount of research has been conducted on pigeon control, but mostly in urban areas. Several studies (Bishop et al. 2003; Rivadeneira et al. 2018; Valerience 2025) have been published addressing strategies for controlling agricultural avian pests, although few are specific to members of the Columbidae family. Additionally, many studies advocate for integrated approaches to pigeon management (Gouge et al. 2022; Klug et al. 2023) but have rarely empirically compared these strategies to individual methods of control. The objective of this study is to review a variety of pigeon control strategies, determine the most effective methods, and identify which of these methods could be applied across both urban and agricultural environments.

2) Comparative Effectiveness of Various Methods of Pigeon Control

2.1) Methods

The effectiveness of various methods of pigeon control was obtained by taking the percentages calculated by studies themselves or calculating reductions in pigeon populations within the study area before and after the experimental period. Papers where reductions could be found or calculated were gathered from a literature search on Google Scholar. Trials from these papers were then categorized similarly to Klug et al. (2023), although visual and auditory deterrents have been combined into “Physical deterrents,” and all lethal control methods have been combined because their mechanisms of control are fundamentally similar. Overall, 32 studies were collected, representing 41 data points in the graph.

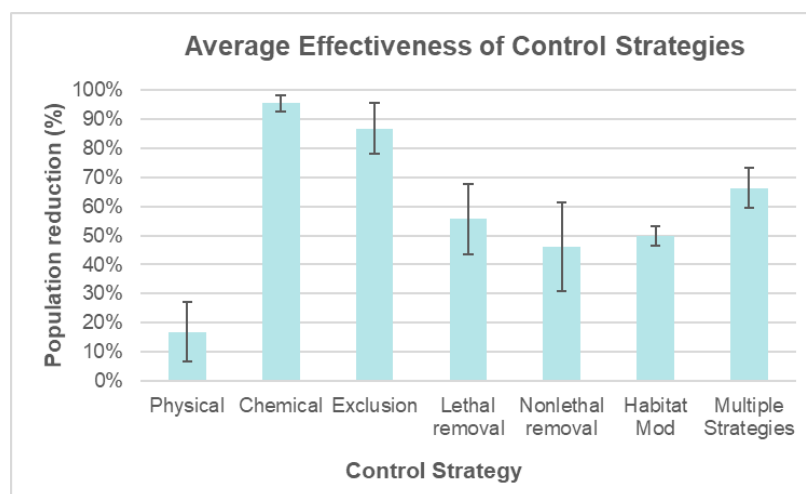


Fig. 1: Mean effectiveness of various methods of pigeon control

2.2) Physical Deterrents

Physical deterrents are auditory and visual devices designed to scare pigeons away from a target location. Auditory deterrents are technologies in which an object is used to scare away nearby pigeons by creating startling or frightening noises. Common strategies include ultrasonic cannons, bioacoustics, and sonic devices. Ultrasonic cannons, which emit sound waves at frequencies greater than 20 kilohertz, such as the BIRD-X Balcony Gard (bird-x.com), have been marketed as a commercial solution to pigeon management by creating sounds inaudible to humans but frightening to pigeons. However, it is well documented that pigeons experience few or no adverse effects from these devices (Goerdel-Leich & Schwartzkopff 1984; Jenni-Eiermann et al. 2014).

Automated sonic devices, like propane cannons, are a common agricultural approach to wildlife deterrence. These devices combust a small amount of propane in a reverberation chamber to create loud and startling noises. Commercial products, like the Zon EL08, can create 130 dB blasts, and can be configured to launch a series of blasts at varying time intervals (Suttonag.com). However, these devices can cause significant noise nuisance, and birds may

habituate quickly, especially when the cannons are deployed in static locations or explode at predictable intervals (Bishop et al. 2003).



Fig 2: The Zon EL08 Propane Cannon (credit: suttonag.com)

Bioacoustics are species-specific alarm and distress calls broadcasted on sonic devices. They have been used with success to deter certain species, such as European starlings (Frings 1964). Habituation to these devices is reduced because the distress calls are also used by pigeons to alert each other about an actual threat. Therefore, there is negative reinforcement already associated with this sound, beyond a simple startle effect. However, Bishop et al. (2003) notes that, similar to sonic devices, “constant exposure to any sound that originates from the same location can quickly encourage habituation as well as causing a noise nuisance to adjacent areas,” making it difficult to use in urban areas. Unfortunately, little research has been done to evaluate the effect of bioacoustics on pigeons, though some commercial technologies have been marketed as solutions. Additional species-specific research may be helpful in judging the full scale of its capabilities and limitations.

Visual deterrents use visual stimuli to scare or intimidate pigeons. One common technique is the placement of models of dead birds or predators, which birds associate with danger. These methods have low upfront costs but limited effectiveness. One study found that gulls fled when dead gull effigies were displayed in an area, but they habituated within a few months (Seamans et al. 2007). Realistic models and consistent relocation of deterrents have been demonstrated to slow the habituation process somewhat (Gouge et al. 2022).

Reflective objects are also commonly used visual deterrents. The Eagle Eyes™ system is a rotating prism that reflects light at pigeons, thereby interfering with their sight during flight. Another approach uses fire flags, which reflect ultraviolet light in a way that appears like fire to pigeons. A commercial reflective gel repellent, designed around the same premise as fire flags, was tested by Stock & Haag-Wackernagel (2014). It significantly reduced pigeon numbers over a 26-day study period, but authors cited slowly increasing landing events in the second half of the experimental period as an indication of slow habituation.

Lasers have also been considered as an option for pigeon deterrence, on the principle that pigeons interpret laser beams as physical objects and avoid them. They offer immediate deterrence without causing physical harm to pigeons. They can be handheld, like the Bird-X Handheld Laser, or automated, like the AVIX Autonomic Mark II (Figure 3). Pyon et al. (2024) found 93% deterrence at dawn and evening using a 1000mW laser at 200m. However, this dropped to just 7% during the brightest hours of the day, most likely due to a reduction in the relative brightness of the laser. However, more powerful tools like the AVIX Autonomic, which claims to be effective at ranges of over 300 meters, may be able to mitigate this issue. A drawback to these more powerful lasers is the threat of eye damage if improperly managed.



Fig 3: The AVIX Autonomic Mark II (credit: birdcontrolgroup.com)

Drones can scare away pigeons by mimicking predator tactics or simply harassing the birds, visually and audibly. Drones have proven to be effective in the field and can be operated autonomously (Hornain & Rosely 2024). Schiano et al. (2021) took this one step further and created an automated pigeon detection system, which reduced maximum pigeon flock stay times on top of a building from 147 to just under 5 minutes.

Overall, physical deterrents, including visual and auditory devices, proved largely ineffective in the studies reviewed, averaging 17% effectiveness in 10 studies. Four static visual deterrents (two different effigies, Eagle Eyes™, and fire flags) were studied in three papers. The effigies were completely ineffective, and the Eagle Eyes™ and fire flags respectively showed a 40% and 33% reduction in pigeon sightings on a study building over 1 year. Handheld lasers (Blackwell 2002; Matsyura 2018) were evaluated in two papers by shining light at pigeon roosting sites with no effect. Ultrasonic devices were tested in two studies, both of which found no effect on the behavior of free-living or captive pigeons. One of these studies also tested a sonic device, which deterred pigeons for only two days before they habituated to the noise (Woronecki 1988; Jenni-Eiermann 2014).

2.3) Chemical deterrents

Chemical deterrents are compounds that can be distributed around an area and cause a reaction that makes pigeons uncomfortable, either physically or physiologically. Polybutane-based sticky gels are applied to surfaces and create an uncomfortable sensation for pigeons. They have been considered as a possible deterrent but ruled out due to potential habituation and ethical concerns that pigeon wings may be glued together (Stock & Haag-Wackernagel 2014). Another compound used is 4-aminopyridine, known by its commercial name Avitrol®, which causes pigeons that ingest it to convulse in a seizure-like motion, thereby scaring flocks away (Swindle 2002). However, according to the manufacturer's website, this compound is toxic to all vertebrate species, and therefore lethal to pigeons when overapplied. Birds affected by lethal doses of this treatment have been reported to fall out of the sky, with many "seizing, convulsing, and screaming before succumbing to the poison" (Sallinger 2021). For these reasons, the treatment carries serious ethical concerns as well as questions of secondary exposure to other animals.

Two more successful chemical deterrents are methyl anthranilate and cinnamic acid. Methyl anthranilate causes mild irritation to pigeons if contacted through the eyes or mouth but is non-toxic to humans. When released as a fog, very low quantities effectively reduced bird numbers up to 500 yards downwind of the source (Vogt 2000). Cinnamic acid, a naturally occurring compound found in cinnamon, has been shown to repel both birds and mammals and can be applied directly to crops (Gill et al. 1995). A key advantage of these methods is that there is an actual nonlethal pain effect inflicted on the pigeons, so they are conditioned with a negative experience and do not return. However, methyl anthranilate photodegrades in 1-2 days, so consistent reapplication is required (Askham 1992). Wind can also blow fogged methyl anthranilate off-target, reducing its efficacy. Two other compounds, methiocarb and cinnamamide (Gill et al. 1995) are both known to be effective on Columbids, although they were not tested specifically on *Columba livia*. For example, Calvi et al. (1976) found methiocarb to be highly effective against picazuro pigeons (*Patagioenas picazuro*), drastically reducing crop damage from 34% to 0.6% on a plot of soybeans. However, neither of these compounds have been experimented with in urban habitats.

Chemical repellents showed some of the highest mean control rates, though only three studies examined the effectiveness of chemical repellents specifically on feral pigeons. Methods of control included tactile and visual gels, and methyl anthranilate. Vogt (2000) demonstrated a 100% control rate after 6 months when airplane hangars were treated with aerosolized methyl anthranilate. Gagliardo et al. (2020) found a 100% effectiveness of a visual gel over 90 days in a field study, while Stock & Haag-Wackernagel (2014) found both tactile and visual gels around 90% effective in a 26-day study period.

2.4) Exclusion

Broadly, exclusion tactics involve using physical barriers to prevent pigeons from accessing loafing, nesting, and foraging sites. Bird spikes are rows of steel spikes used to cover

ledges and loafing spots, thereby making these areas unappealing to land on. They have proven highly effective at reducing local pigeon presence when properly installed (Harris et al. 2016), as birds risk injury if they land on the spikes. Similarly, bird wire makes perches unusable by stringing wire a few inches off the landing surface (Thomas et al. 2007). However, the U.S General Services Administration notes that bird spikes may collect debris and that wire is only effective on small areas, like ledges.

One exclusion method used more commonly in agricultural settings is netting, which can be used to cover specific rows of crops or entire fields (Taber 2002). This method physically prevents birds from reaching the target area and has a near 100% success rate. Netting has been used successfully on fields of grapevines and blueberry bushes. Bagging individual plants has proven similarly successful (Karajeh 2018) for similar reasons. Potential drawbacks include restricted access to crops for growers (Taber 2002) and high costs due to acquisition and maintenance of nets and netting equipment.



Fig 4: Bird netting on grapes (credit: Fir0002, Wikimedia Commons, 2005)

Exclusion deterrence methods reduced pigeon presence in study areas by an average of 87%. Bird deterrence methods included bird spikes, bird wire, and blocking structures. Harris et al. (2016) found pigeon spikes to reduce pigeon sightings on a building by 70% over 1 year. Andelt & Burnham (1993) concluded that bird wires were 90% effective, though successful landing slowly increased throughout the 5-hour study period. Seamans et al. (2007) found 100% deterrence in a captive environment over 4 days using BirdBlox™, a blocking structure utilizing a thin plastic strip that makes surfaces too thin for pigeons to land on. Although these methods are effective, they are limited in the total area that can be covered.

2.5) Habitat Modification

Habitat modification strategies center around altering the inherent construction of an environment, instead of adding additional control methods. Building design is one area where considerations can be made to reduce pigeon densities. Haag-Wackernagel & Geigenfeind (2008) found that medium-sized pigeons were able to squeeze through square gaps of 7 cm and were

able to perch on surfaces of just 5 cm. The authors concluded that angling of surfaces and reduction of ledge widths were key to preventing pigeons from landing.

Food source reduction has long been considered as a strategy to reduce pigeon numbers. In urban areas, a small number of individuals who feed pigeons can prop up enormous populations, such as in Melbourne, where one individual was reported to bring in enough feed each day to feed 3000 pigeons (Felder 2007). The city of Basel, Switzerland, is considered a classic example of success for its use of a highly effective public education campaign that reduced the pigeon population by 50% after 4 years, providing a sustainable framework for pigeon management (Haag-Wackernagel 1995). Similarly, a campaign in Barcelona to reduce pigeon feeding saw a precipitous 40% decline in pigeon numbers over the course of a year (Senar et al. 2010). However, achieving public compliance may be difficult, as the most prolific bird feeders are often reluctant to change their habits.

Dovecotting is a habitat modification technique that involves the creation of artificial nesting locations in areas where pigeons already roost or feed. When eggs are laid, they are replaced with fakes, thus inhibiting pigeon reproduction (Haag-Wackernagel 1995; Dobeic et al. 2009). Of course, this method requires constant human interaction in addition to the construction of many dovecotes, which can be quite expensive.

Habitat modification studies found 40-55% declines in pigeon presence, with study periods between 10 months and 8 years. All three papers (Stock & Haag-Wackernagel 2016; Senar 2017; Soh 2021) were field studies of food reduction to reduce carrying capacity. These papers suggest food reduction can be lastingly effective so long as the barrier of public compliance for food reduction can be overcome.

2.6) Lethal Control

Removal strategies involve the direct reduction of pigeon numbers, either through lethal or nonlethal methods. Avicides, like Starlicide, are lethal compounds that are applied to bait, which is then consumed by problem birds. Eisemann et al. (2003) found that the LD50 (The dose at which 50% of birds died) of Starlicide on feral pigeons was <20 mg/kg, roughly the weight of five grains of rice. In addition to ethical concerns around lethal control methods, Starlicide may also have effects on non-target bird and fish species.

Trapping utilizes bait or decoys placed in metal cages or nets to capture pigeons, where they are held until the trap is checked. Birds are then relocated or killed, though relocation is often impractical because of pigeons' homing capabilities. These devices are highly targeted because birds of non-target species can simply be released (Farfan et al. 2019). Relative to some other methods of lethal pigeon control, cage traps require relatively less maintenance due to their passive nature, as Teffo et al. (2022) observed. However, static trapping exerts selective pressure against more adventurous pigeons, which are more likely to explore traps. Over time, these pigeons will be removed from the population, and remaining individuals will be less likely to enter traps. Whoosh nets, which use elastic cords similar to bungee cords to propel nets over a target area, have been tested and found to be effective. Nets can capture both adventurous and

non-adventurous pigeons, avoiding the selective pressure of static traps (Coxen et al. 2018). However, unlike static traps, whoosh nets typically require human input and a flat space for operation.

Shooting is a classic method of pigeon control, though it is only applicable when there is no risk of harm to humans and infrastructure. Hoy and Bivings (1987) demonstrated that shooting could effectively manage pigeon numbers in Stuttgart, Arkansas. Hunting events had to be conducted annually but costs were not exorbitant due to voluntary participation. However, pigeon numbers began increasing again immediately after the hunt, so this method is only effective when continuously applied.

Biological control from raptors is an appealing option because it puts pressure on pigeon populations while also serving as a deterrent, since pigeons recognize the threat and do not return as long as the raptor is present. Trained falconers may be deployed on demand to deter birds in urban areas or in agricultural contexts (Teffo et al. 2022) and scare or kill pigeons as needed, though the effect of a single raptor is often more deterrent than lethal. Alternatively, Valerience et al. (2025) describes Malaysian farmers raising perches and encouraging local predation by black-winged kites to deter pest bird activity, and Felder (2007) notes a successful raptor nest deterring pigeon activity on a bridge in Connecticut. While effective and requiring little maintenance, this type of management is dependent on raptor presence in the area, which is difficult to control.



Fig 5: Hooded adult and juvenile Peregrine Falcons, commonly used in falconry (credit: El7bara, Wikimedia Commons, 2005)

Overall, lethal control methods had an average of 48% effectiveness, with a range of 0-93% and study periods of 24 days to 7 years. Two studies (Hoy & Bivings 1987; Phillips et al. 2012) found that shooting was effective for managing pigeon populations, though one (Phillips et al. 2012) was an eradication campaign on an isolated island. Two more studies (Kreps 1979; Blanton et al. 1991) examined the effectiveness of 3-Chloro-4-methylaniline (Starlicide) on pigeons and saw 50 and 93% reductions in pigeon populations respectively. The last two studies examined trapping techniques, like netting or cage traps. Farfan et al. (2019) observed a 50% reduction in pigeon presence using cage traps, but Sol & Senar (1992) argued that a trapping campaign in the city of Barcelona over seven years caused no significant change in population. Even though 5 out of 6 studies found lethal control effective, there are many factors that make these methods less than ideal. One major drawback is high ongoing costs because culling must constantly be performed to keep populations in check. After culling, pigeons from other areas will often immigrate into the targeted area, thus quickly repopulating the culled region (Sol & Senar 1995). In some studies, dealing with pigeon corpses was a significant drawback for tools like avicides or firearms, especially when used in population-dense environments. Lethal treatments can also be intrusive. Hoy and Bivings (1987) reported that the entire town of Stuttgart, AK, was closed to traffic to facilitate a yearly pigeon hunt.

2.7) Nonlethal Control

Fertility control has been considered as an ethical solution to reduce feral pigeon populations because no live animals are killed. The leading technology in this field is nicarbazin, a chemical compound commonly marketed as Ovocontrol® or Ovistop®. This product is applied to pigeon feed and must be fed to pigeons daily while pigeon control is necessary, or the compound will not reach necessary levels and will dissipate over time. It is theorized to work by changing yolk pH (Klug et al. 2023) or inhibiting the ZP3 sperm receptor (Reinoso 2008). It has been used with general success. In Barcelona, for example, pigeon populations declined about 12% per year throughout the study period, and another positive result was reported in Genoa (Gonzalez-Crespo 2022; Albonetti et al. 2015). Drawbacks include a high cost and significant human effort required to distribute the feed in large metropolitan areas. The Ovocontrol website recommends one pound of feed per 80 pigeons every day. In cities with tens of thousands of pigeons, costs can increase rapidly, as each pound of feed costs approximately \$9.10 (Ovocontrol.com).

Vasectomy has been proposed as a method of fertility control, demonstrating 99% sterilization (Heidereich et al. 2015); however, it is highly impractical because each bird must be trapped and undergo a surgical procedure.

Nonlethal control methods demonstrated an average effectiveness of 46% from 4 studies. Nicarbazin treatment was tested in all of these. Three of the studies (Senar et al. 2021; Gonzalez-Crespo & Lavin 2022; Albonetti et al. 2015) were field studies in which pigeons were fed nicarbazin-treated bait over a period of 1-8 years. The fourth study (Avery et al. 2008)

described a small laboratory experiment in which 22 pigeons were fed nicarbazin-coated feed, and at 116 mg/kg, 100% control was achieved.

2.8) Multidisciplinary approaches

Broadly, multidisciplinary approaches performed reliably, resulting in an average pigeon reduction of 66%. All 10 studies concluded that their methods were effective, indicating desired outcomes were consistently achieved. Different environments require different approaches, so combinations of multiple strategies were usually well adapted to the environment, whether managing a single building or an entire city. One possible explanation for high average performance is reduced habituation, because more methods are used at once, thereby creating a dynamic threat for the pigeons.

2.9) Other Considerations

While change in pigeon concentrations is an important metric for pigeon control strategies, other issues such as costs, scalability, and long-term effectiveness are important to note when considering the most effective method of control in a given scenario. Chemical repellents and exclusion deterrence are highly effective in areas where small-scale deterrence is necessary, like on rooftops or ledges. However, scalability for many of these technologies is limited because they cannot reduce carrying capacity, so pigeons may congregate on other structures instead. These technologies are recommended for use on individual buildings, airports, or other individual structures where bird presence would be of particular harm or nuisance. Nonlethal deterrence and habitat modification had the longest study periods (up to 8 years) and were generally proven effective in the long term. Nicarbazin fertility control is effective but has high continuous costs, estimated at 33.6 euros per pigeon per year by Gonzalez-Crespo (2023). Habitat modification studies were ethical, scalable, and cost-effective as long as food reduction was maintained, making it difficult to implement initially but cheap and sustainable if enacted effectively.

Physical and lethal deterrents are not recommended due to their poor long-term effectiveness. Lethal control is fraught with ethical concerns, ongoing costs, and difficulties in permanently reducing large populations to tolerable levels. These are recommended for government-level control campaigns, though they may not be helpful on an individual level (Dobeic et al. 2011). Physical deterrents are cheaper and more ethical, but largely ineffective, as no study found more than 40% reduction in population and several studies found no effect from these deterrents. Multidisciplinary methods were effective, though methods of control, cost, and sustainability varied widely. Because every environment is different, multidisciplinary approaches are likely the most effective overall because they can take advantage of the strengths and avoid the weaknesses of different strategies based on local conditions, although they are surpassed by other methods in specific circumstances.

3) Crossover Applications/Future Directions

Although prior research has focused on either urban or agricultural environments, finding pigeon control methods that can be applied across both should be investigated. Urban and rural environments often border each other, and pigeons may travel back and forth between areas, causing nuisance across urban-rural boundary areas (Johnston & Janiga 1995; Skead 1969). Fig. 6 categorizes strategies that could be effective at urban-rural boundary areas. Here, the limitations and future applications of various methods of pigeon control are analyzed from the nature of urban and rural environments.



Fig 6: Pigeon control strategies applicable in urban and rural environments.

Bird wire, gel repellents, managed dovecotes and bird spikes are difficult to scale to large areas, making them impractical in agriculture. Building modifications cannot be conducted on large crop fields. Managed dovecotes do not control pigeon predation of crops. Nicarbazine requires the consumption of treated bait by pigeons and would be prohibitively expensive if applied to fields. Trapping is likely ineffective in agricultural environments due to higher population dispersion and widespread food availability, negating the incentive to enter the traps. Effigies and reflectors are applicable across the urban-rural gradient because they can be placed on posts in agricultural areas or on buildings (Birdbarrier.com). Drone deterrence technology has been tested in both urban and agricultural environments (Wang 2021; Schiano et al. 2021), indicating that the drones' ability to navigate through space is widely applicable. Although lasers have mostly been used in agricultural settings, one study did find a temporary deterrent effect by lasers from urban roofs and ledges on buildings (Gorenzel et al. 2010). Exclusion netting has been used successfully in agricultural settings (Taber 2002) and is commercially advertised for use in urban areas (birdbgone.com). Compounds like methyl anthranilate have mostly been assessed in flat, low-density areas, like farms or airports. While applications to the urban environment have not been studied, fogging could be an effective solution for area deterrence, provided the compound is not blown away from target areas by wind. Natural predation and falconry can be effective across environments because falcons can hunt in both situations (Teffo et al. 2022; Rivadeneira et al. 2018). Artificial intelligence is applicable in all environments

where cameras can be installed to identify pigeons autonomously, aiding targeted deployment of control strategies.

Avicides like Starlicide and Avitrol are unlikely to be useful in urban environments because birds may die in high-density urban environments, where they may frighten humans (Dodge 2021). Shooting in urban areas is dangerous because projectiles may hit infrastructure, other animals, or humans. Noisemakers are difficult to use because of the din of city activity and nuisance to humans. Research has demonstrated success in changing the sowing depth of plant seeds in agricultural environments to reduce crop losses, but this is not applicable to urban environments.

4) Future Directions

Lasers, drones, and artificial intelligence are all novel methods of pigeon control. These methods have been studied but require more research to become commercially viable. However, they have potential to become highly effective deterrents in both urban and agricultural environments if certain obstacles are overcome.

4.1) Lasers

Studies on low-powered handheld lasers (Blackwell et al. 2002; Matsyura 2018a) have demonstrated that they are not particularly effective on pigeons, as the birds quickly habituate. More recent experiments with advances in technology, such as higher-powered lasers, different light wavelengths, and irregular movement patterns, have demonstrated the effectiveness of laser technology as a nonviolent bird repellent (Elbers & Gonzalez 2021). More research is needed to examine species-specific effects, especially for pigeons. No studies have been conducted on pigeons specifically, and this carries significant consequences for applicability in urban environments. For example, evaluating the sensitivity of pigeons to different strengths of lasers at close ranges, especially in environments with light pollution, would be key.

4.2) Drones

Drones have been investigated as a method of pigeon control for several years due to their ability to move in the air, which makes them more targeted and dynamic. Schiano et al. (2021) described a repellent system that leveraged a neural network pigeon identification system and an autonomously dispatched drone, which was effective in deterring flocks of pigeons from the top of a building. Another novel application involves the ability for drones to carry other methods of bird control, such as bioacoustics (Wang 2021) or perhaps lasers, making them a responsive and unpredictable tool for bird control and negating one of the biggest issues associated with static deterrents. Although commercially available systems have yet to be developed, AI technology could be paired with drone systems to deliver highly targeted deterrence at the appropriate time. Currently, drones may be easier to apply in agricultural environments because there are fewer constraints on their movement, but if barriers like

licensing and audiovisual nuisance can be overcome there is great potential for urban implementation.

4.3) Artificial Intelligence

The development of artificial intelligence could represent a significant enhancement to pigeon control strategies, particularly with regards to image recognition. Guo et al. (2024) created a pigeon detection model that was able to identify pigeons in a variety of poses and backgrounds. While AI models cannot be used to deter pigeons on their own, they can multiply the effects of other technologies by identifying the exact location and number of pigeons through a camera feed, allowing deterrents to be dispatched quickly and precisely. Although the model used in Schiano et al. (2021) occasionally under or overestimated the number of pigeons in the frame, it was still effectively able to identify the arrival of flocks and prompt the deployment of the drone, illustrating that the model does not have to be perfect to be effective. Other opportunities to use AI might include creating models to predict pigeon hotspots based on particular characteristics of structures within an urban environment, or the identification of agricultural food sources that may attract pigeon populations. Preemptive strategies such as building modifications or even intermittent deployment of chemical repellents could be deployed in order to prevent the congregation of pigeon populations in certain “high risk” areas.

5) Conclusion

Of the methods reviewed in this study, gel repellents (95%) and pigeon spikes and wires (87%) were the most effective at point deterrence, while nonlethal control (46%) and habitat modification (50%) were less effective but more scalable and sustainable. However, most control methods have drawbacks and are situational, so when used in combination with each other they may synergize to overcome the disadvantages of each individual methodology. There were also some limitations in the scope of this study. For example, variation in the duration of studies analyzed ranged from a few hours to a few years, potentially affecting average effectiveness. Different studies also controlled various sizes of populations, and smaller studies may have had higher effectiveness due to the insular nature of these populations, which prevents migration and makes it easier to target all birds with deterrence or control measures. Finally, the number of studies was relatively small, and some categories had only three or four studies. More studies may be needed to increase the accuracy of the data. Future research directions should include further investigating the potential of machine learning algorithms, lasers, and unmanned aerial vehicles to more quickly and effectively target and deliver deterrence.

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Caught in the Web: A Comprehensive Review of Internet Addiction's Impact on Adolescent Mental Health By Rita Zhou

Abstract

Internet addiction (IA) is characterized by excessive and compulsive internet use that impairs daily life and social interactions. As digital connectivity is being integrated into modern society, the prevalence of IA has increased significantly, primarily among youths and young adults. This article presents a review of the literature that exists on IA, its global prevalence, its associated risk factors, and how it impacts mental health. The study deals with various diagnostic criteria as well as classification systems, highlighting the ongoing challenges in standardizing IA as a clinical disorder. The discussion addresses common comorbidities, including substance use disorders and attention-deficit hyperactivity disorder (ADHD), that regularly co-occur with IA. Additionally, this article evaluates existing treatment approaches, ranging from cognitive-behavioral therapy (CBT) and pharmacological interventions to behavioral modification programs and digital detox programs. Understanding the underlying factors is essential in devising evidence-based treatments and public policy for averting the negative consequences of IA and promoting healthier internet use habits.

Introduction

The internet has radically transformed and revolutionized nearly every aspect of human life. There is now a new era of efficiency and connection. With a few clicks or taps, individuals can easily access enormous databases of information and get tasks done with unmatched speed. People are also connected with others across the globe in an instant. However, technological integration has introduced a range of psychosocial and behavioral challenges, one of the most pressing being internet addiction. As more and more people rely on the internet, so too have concerns regarding its potential to create compulsive and unhealthy use.

Internet Addiction (IA), also referred to as Problematic Internet Use (PIU), has derailed people's lives to the extent where they spend excessive amounts of time surfing the web for entertainment. This obsession greatly affects day-to-day life by disrupting a person's work, academic obligations, and even personal or family relationships. IA is distinct from chemical addictions in that it is a behavioral problem arising from the very nature of the internet itself. The virtual world, in particular, exacerbates these behaviors via mechanisms that exploit human intellectual and emotional vulnerabilities. Features like infinite scroll, algorithmic feeds, and social feedback loops are all common on the internet and engineered to produce a form of behavioral conditioning that can lead to habitual overuse (Young, 1998). This is especially concerning among children and young adults, who are developmentally more vulnerable to such use.

Adolescents not only constitute the highest number of net technology consumers but are also exposed to excessive psychosocial pressures, such as academic demands and identity formation that increase their susceptibility to excessive internet use (Cheng & Li, 2014). There

have been numerous studies that refer to disproportionately high rates of IA among young people. Teenagers and university students tend to have patterns of overuse of the internet that interfere with school achievement and offline social relationships. These patterns are readily neglected or dismissed as commonplace behavior in a digitally saturated society, making early detection and intervention even more challenging. The threat is also intensified by the fact that self-regulatory abilities are not yet fully formed during adolescence, hence rendering youths less able to control their own online behaviors without official guidance (Pjevac et al., 2024).

Research on Internet addiction began in 1994, and it was first proposed by American psychiatrist Ivan Goldberg in 1995. Soon after that, American psychologist Kimberly Young (1998) developed the world's first criteria for diagnosing Internet addiction. She proposed that Internet addiction be labeled as a symptom of impulse control disorder of internet users, rather than an independent psychiatric disorder. Her work laid the groundwork for subsequent research and clinical discussion of excessive internet use.

Despite its increasing visibility and literature base, IA remains controversial among the clinical community owing to the absence of standard definitions and diagnostic criteria. For this reason, the present paper uses the term “Internet Addiction” rather than “Internet Addiction Disorder.” While it shares many of the clinical features of other established behavioral addictions like gambling disorder, it is not formally named a distinct disorder in the *Diagnostic and Statistical Manual of Mental Disorders* (DSM-5) or the *International Classification of Diseases* (ICD-11). The only exception is Internet Gaming Disorder, which in the DSM-5 appendix is prescribed as a disorder that warrants further research (American Psychiatric Association, 2013). This official non-classification presents barriers to proper diagnosis and evidence-based treatment protocol development.

To bridge this gap, the present review seeks to provide an integrative summary of the Internet Addiction literature, with special reference to enhanced susceptibility among adolescents and young adults. The article touches upon the most salient risk factors of IA and its psychiatric effect and the most common comorbid psychiatric disorders like depression and ADHD. It also examines current treatments, from cognitive-behavioral therapy to family-based therapies, and provides future research and policy recommendations to slow the increasing public health cost of pathological and compulsive internet use, particularly in the younger generations.

Prevalence of Internet Addiction

The prevalence of Internet Addiction varies significantly across studies, mostly due to differences in diagnostic criteria and population groups. The most frequently cited meta-analysis by Cheng and Li (2014) estimated the global prevalence of IA at around 6.0%, with substantially higher rates in Asian nations compared to Western cultures. Regional variations are often explained by the access levels to the internet, where increased internet use is normally associated with increased risk of problematic behavior (Cheng & Li, 2014). Additionally, students in some regions have increased academic stress and demands, which may be a contributing factor to extended screen time. Attitudes towards technology also vary between cultures. For example, in

some cultures, overuse of the internet is deemed typical and acceptable in culture terms, while other cultures feel differently. Such cultural attitudes may guide whether or not internet use is controlled and perceived and ultimately may shape the aggregate risk of internet addiction.

In the US, it's found that 85% of adults report using the internet on a daily basis, and perhaps most remarkably, 31% say that they are online "almost constantly" (Pew Research Center, 2021). Although such intensive internet use is not in itself by definition addiction, such persistent use must surely call into question normalization of behavior. As digital technologies have entered so fully into everyday life, the bar for what counts as "excessive" use has been raised. This effect of normalization can filter out early warning signs of pathological use, particularly in environments where there are no digital borders or educational elements on the use of healthy screens. Other studies have shown that this widespread use is not limited to adults. That's based on Common Sense Media in reports that they use a total of over 8.5 hours a day on screens for entertainment alone, excluding any school or homework screen time (Rideout et al., 2022). This additional excessive usage will further enhance exposure to compulsive behavior and will necessarily crowd out time that would otherwise be used for sleep, exercise, or face-to-face socializing. In the absence of structure, modeling, and parental training in digital literacy and moderation, the boundary between healthy use and addiction is circumvented. Consequently, the threat potential for IA may be much more widespread than current public awareness reveals.

Globally, the tendency is even more apparent in younger age groups. Figure 1 illustrates the distribution of internet addiction severity levels based on a 2020 study (Vejmelka et al., 2020). It shows that 37.25% of participants had no signs of addiction, while 3.73% exhibited a high level of addiction. This highlights the growing concern of problematic internet use among youth in residential settings. Another study in Nepal demonstrated that 29.9% of the undergraduate students surveyed fell somewhere in the range of internet addiction (Acharya et al., 2023). Rates were even higher among males and very frequent users of social websites and video-sharing websites. This is in line with broader trends that place adolescents and young adults at increased risk due to their greater exposure to digital technology and lack of fully developed self-regulation capabilities. Moreover, Gaming Disorder, currently officially accepted by the WHO in ICD-11 as a clinical condition, is a special form of IA. Based on 53 studies conducted between 2009 and 2019, an estimated global prevalence of 3.05% was cited for Gaming Disorder by a systematic review (Stevens et al., 2021). Once again, the disorder has higher prevalence in East and Southeast Asian cultures where gaming is more embedded into youth lifestyle and recreational norms.

The above findings highlight the growing global concern about IA and the need for culturally sensitive diagnostic tests and interventions. While prevalence estimates are inconsistent, upward trends in digital consumption and the increasing number of individuals, particularly young people, showing signs of compulsive online behavior indicate that IA is turning into a significant public health challenge. Without standardized assessment tools and focused intervention programs, many people at risk might remain undiagnosed and untreated.

Therefore, IA should be recognized not just as a clinical issue but as a public health matter that needs immediate attention and a coordinated global response.

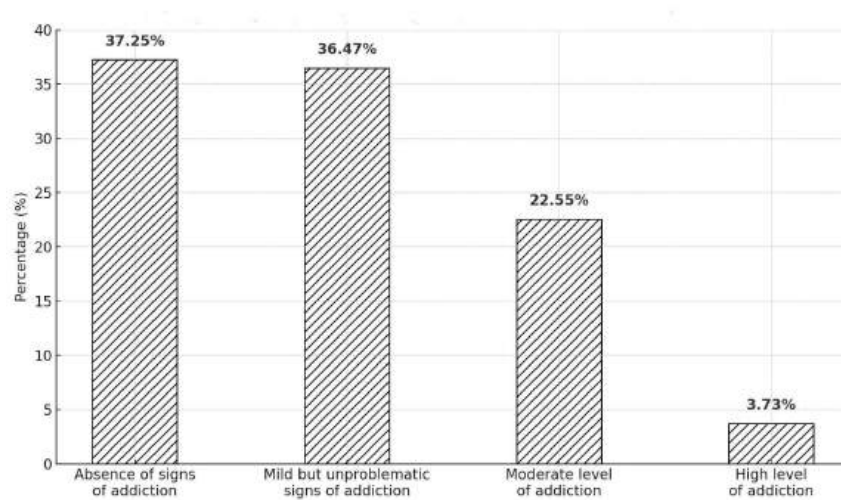


Figure 1. Prevalence of Internet Addiction by Severity Levels among Youth in Croatian Dormitories. Based on Vejmelka et al. (2020), the chart shows that 37.25% of participants had no signs of addiction, while 3.73% exhibited a high level of addiction.

Risk Factors

Internet Addiction is a complicated disorder that is influenced by a combination of demographic, psychological, and environmental factors (see Figure 2). Understanding how these factors interact is important for identifying individuals who may be at-risk and for developing effective prevention and treatment strategies. Clearly, an integrated approach is necessary to tackle the issues. It should include psychological screening for early identification of at-risk individuals, family education for supportive family climate, and the promotion of digital literacy to develop healthier internet use and self-regulation. These components of a strategy to manage IA can provide a stronger defense against the increasing worldwide threat of IA. The following sections provide a closer examination of the key risk factors, supported by recent research and global data.

Demographic Factors

Demographic characteristics such as age, gender, and socio-economic status play a significant role in the development of Internet Addiction. Research has consistently shown that adolescents and young adults are most vulnerable to IA (Kuss et al., 2014). This vulnerability is due in part to their extensive use of digital devices, not only for educational purposes but also for activities that often lack structured time limits such as social networking and gaming. Moreover, young individuals typically exhibit underdeveloped self-regulation skills, making them more prone to the problem (Anderson et al., 2017). The study from Nepal further indicated that students aged 18 to 22 had a greater toll from IA than younger students (Acharya et al., 2023). This age group represents emerging adulthood, which is a transitional stage with increased

independence, identity exploration, and emotional instability. Their ability to develop and use self-regulatory mechanisms is further impaired by access to the unrestricted internet. This study underscores the need to develop prevention and intervention initiatives for IA for specific demographic categories, especially among young people transitioning from adolescence to adulthood.

Gender differences have also been identified frequently in IA study, especially in terms of specific behaviors leading to the issue. Research indicates that males are at greater risk for IA, with some showing a higher tendency to develop Internet Gaming Disorder (IGD) (Király et al., 2018). A recent comprehensive review found that roughly 8.5% of males exhibited clinical symptoms of IGD, while evidence of such symptoms in females was only at 3.5% (Kim et al., 2022). Such male to female disparity is likely due to different patterns of digital media engagement by them. Males are prone to engage with the internet through competitive, action-oriented, hardcore, multiplayer online games, which are designed to be immersive and invite prolonged play. These games have features like ranking systems, in-game rewards, and social interaction through avatars, all of which encourage excessive, compulsive use. In contrast, females are more likely to use the internet for social reasons, such as chatting and posting in social media, which usually rely less on reinforcement and addictive feedback loops. Therefore, the pattern of behavior by gender reflects that IA describes not only the amount of time engaged online, but also the nature of the engagement.

Variations in regional and cultural factors further complicate the understanding of Internet Addiction. Among populations worldwide, the prevalence of IA varies considerably. An extensive research review from Europe and Asia found an IA prevalence across countries ranging from 0.7% to 15.6% (Kuss et al., 2014). Differences in digital infrastructure, education systems and standards, parental supervision, and cultures regarding technology use can account for the variations. For example, in South Korea, where digital infrastructure is highly developed and academic competition is intense, the adolescent populations have an IGD rate of 16.1% (Jo et al., 2021). Conversely, the IGD rate of the United States is 8.5%. The expectation is that gaming platforms and internet access in the United States is much more extensively accessible, which might lead parent attitudes toward more screen time for children as a cultural norm (Király et al., 2018). Conversely, Germany and the Netherlands reported significantly lower rates of IGD being 1.2% and 5.4% respectively. This could indicate more digital literacy education, structured educational systems, societal or familial norms, or that IA is simply less prevalent in those countries. Differences in cultural context must be accounted for when identifying IA and developing population specific prevention and intervention programs. What works in one country or community may not apply to another due to cultural and contextual factors. Therefore, these factors should always be considered in public health approaches to this issue.

Socioeconomic status (SES) has also been linked to the development of IA. But there is a mixed and sometimes contradictory body of literature on the topic. In some studies, scholars noted signs and inferences that adolescents and young adults from lower SES backgrounds may be at greater risk based on heavy reliance on the internet for entertainment and socialization

(Smahel et al., 2020). The suspicion was that limited access to other activities, combined with lower levels of parental monitoring and academic expectations, nurtured greater unhealthy digital habits among these youth. In other studies, however, researchers suggested that youth from higher-income households might be more likely to develop IA due to greater access to internet-connected devices, with parental monitoring also being limited in such contexts (Chemnad et al., 2023). In particular, the use of more advanced technology (incorporating multiple devices, virtual reality, gaming consoles, etc.), which is rapidly becoming more normalized in higher SES contexts, paired with fewer restrictions on screen time indicated a high level of concern for adolescents' online experiences. The SES considerations on two sides of the socioeconomic dichotomy highlight the distinct roles of deprivation and access in assessing IA. They prompt reflection on questions such as "when does appropriate use cross the line into overuse?" as well as other relational aspects of the online/offline experience.

Psychological Factors

A growing body of research supports the role of psychological traits in the onset and course of Internet Addiction. Personality traits such as impulsivity, neuroticism, perceived low self-worth, and social anxiety have been shown consistently to be negatively correlated with high internet use (Andreassen et al., 2017; Kuss & Griffiths, 2015). These traits are often related to limitations in behavioral regulation which allow for compulsive patterns of internet usage. Based on instant gratification and a social-reinforcement model, the internet may provide a temporary coping response for those with psychological vulnerabilities, thereby reinforcing addictive use habits across time.

Beyond personality traits, having an existing comorbid psychiatric condition is also a risk factor for IA. For example, in a survey study (Acharya et al., 2023) conducted amongst individuals identified in clearly IA, 29.4% were high in perceived stress, 4.9% showed depressive symptoms, and 29.4% had low self-esteem (see Table 1 for a summary of key psychological symptoms and their implications). These results may indicate that mental distress not only is an outcome of problematic internet use, but it also contributes to their engaged problematic use. Physical symptoms that were reported attributed to low and disrupted sleep and excessive screen time were also common, with 26.8% of respondents endorsing insomnia, 20.0% reporting daytime drowsiness, and 19.0% indicating eye fatigue. Thus, it is reasonable to infer that these conditions can worsen and create difficulties for mental health, with the result that internet use serves to both fuel psychological and physical symptoms and as escape from those same aspects.

Further empirical support comes from a population-based study (Cha et al., 2023) that quantified the psychological risks of IA using odds ratios. The study demonstrated strong associations between IA and several psychological issues, including: perceived stress (OR: 0.70; 95% CI: 0.62 – 0.79); dissatisfaction with sleep (OR: 0.73; CI: 0.62 – 0.79); depressive symptoms (OR: 0.62; CI: 0.55- 0.71); suicidal ideation (OR: 0.57; CI: 0.48-0.68); and alcohol use (OR: 0.53; CI: 0.47-0.60). These data provide compelling evidence of the strong link

between IA and both internalizing disorders like anxiety, and outwardly-focused behaviors like substance use issues.

The above findings collectively affirm the understanding that IA should not be examined in isolation. Rather, it should be viewed within a larger psychological picture. Many individuals with IA may be seeking maladaptive emotional regulation strategies by utilizing the internet to avoid their unresolved emotional issues or chronic problem-based stressors. Therefore, effective interventions must consider psychological and pathological adopting behaviors, rather than simply developing a plan to regulate behaviors related to IA. It is essential to develop prevention and treatment frameworks that include effective and sustainable strategies that go longer than just short-term behavioral intervention.

Environmental and Social Factors

The environment influences Internet Addiction through various factors. Such factors range from family structure and peer relationships to academic challenges and beyond. Families can operate in a dysfunctional manner, where poor parental supervision, lack of rules or ineffective communication allow internet use to go wild and unchecked. In these families, children and adolescents can develop unhealthy online habits as a result of poor counseling or direction. A recent study (Cha et al., 2023) that screened children for IA showed that 24.7% had no parent control, 54.4% had partial parent control, and only 20.9% had regular parent supervision. The figures indicate the reality that active family engagement is critical in affecting positive digital behavior. Parent or caregiver non-involvement might subject youth to overuse, and therefore organized family-based measures are necessary in IA prevention and intervention.

Outside the domestic setting, peer relationships are also a strong source of IA, especially among adolescents. At this level of development, social validation and peer affiliation become focal concerns. Teenagers generally suffer from a chronic sense of needing to remain online, or else they will be out of the loop, something often called FOMO (Fear of Missing Out) (Tandon et al., 2021). Obsessive use of gaming communities, social media, and messaging media emerges from this pressure, in which online presence is directly linked to social standing and being part of the group. The obsessive needs to maintain these connections can begin to obscure the line between healthy interaction and addiction. Over time, this constant connectivity may erode real-world social skills, leaving individuals more dependent on virtual affirmation for their sense of belonging and identity.

Schools are also implicated in the digital world in ways that inevitably encourage IA. Though technology has opened up learning possibilities in many ways, it also fosters a world where screen time is a necessity, rather than a discretionary entertainment. Increased reliance on digital resources to learn, coupled with increasingly large volumes of homework and academic rivalry, further ties students to their screens. This constant academic screen exposure often blurs the boundary between educational and recreational use, making it more difficult for students to self-regulate their time online (Shanmugasundaram & Tamilarasu, 2023).

In addition to the institutional and interpersonal conditions, broader structural conditions, such as screen-centered and urbanized lifestyles, organize patterns of internet usage. Urban youth, often living in areas with limited or no access to outdoor recreation, may possess no viable alternatives to virtual play. The ubiquitousness of screen-based routine, from education to social life, secures dependence on virtual environments, with minimal room for exploration of real environments or physical exercise. This lack of offline stimulation not only reinforces digital immersion but may also contribute to delayed social-emotional development and increased feelings of isolation. Over time, such environments can normalize excessive screen use as a default lifestyle, making early intervention even more difficult (Evans & Buil, 2018).

Further evidence of the environmental impact on IA is found in the work of Monteiro et al. (2023), where 340 adolescents between the ages of 12 and 17 were interviewed to examine the correlations between Internet Addiction, sleep, and family communication. The findings were striking: 64.1% of the participants exhibited mild to moderate IA. It also demonstrated a positive correlation with day-time sleepiness, and a negative correlation with effective family communication. Youth were more prone to have disrupted internet use, and female participants were more prone to report heightened day time drowsiness. This study emphasizes the significance of the inclusion of sleep hygiene education, increased physical exercise, and proper communication patterns in families as part of prevention efforts targeted at avoiding the degenerative health effects of IA among youth.

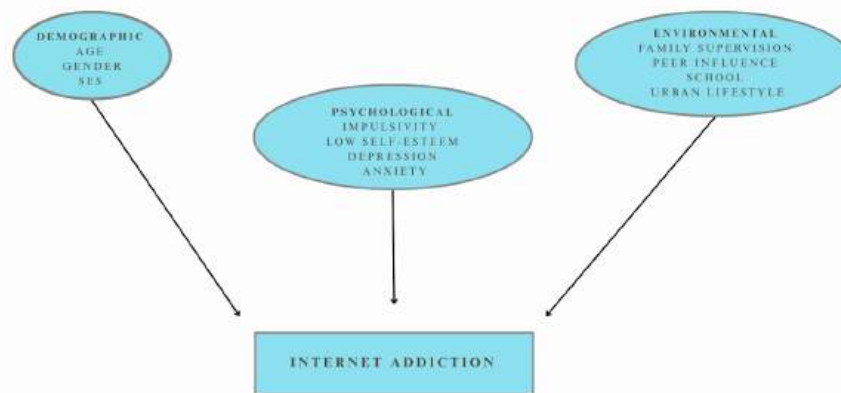


Figure 2. Interaction of Major Risk Factors Contributing to Internet Addiction.

Diagnostic Criteria

Despite the growing recognition regarding Internet Addiction as a widespread issue, to this point no consensus diagnostic criterion exists for differentiating and treating the condition. The absence of such consensus greatly diminishes effort in a number of fields such as clinical diagnosis, cross-cultural comparability of study outcomes, and evidence-based treatment protocol construction (Pan et al., 2020). Currently, the diagnostic criteria of IA borrow primarily from models of substance use disorder and other behavioral addictions, such as gambling

disorder. Such models tend to be centered on psychological and behavioral symptoms, including preoccupation with internet use, withdrawal upon restriction of access, tolerance (i.e., progressively increased use in an effort to achieve the same satisfaction), and continued unsuccessful attempts to control or reduce internet use (Young, 1998).

So far, the most widely used instrument in clinical and research environments is Young's Internet Addiction Test (IAT), which was developed in the late 1990s. The IAT is a 20-item self-report instrument designed to assess the severity of compulsive internet use and the degree to which internet use impinges on a person's life. While it has proven to be a common measure for the evaluation of IA, its threshold scores have been differently interpreted in research studies as well as across cultures (Király et al., 2018) (see Table 2 for a comparison of major diagnostic instruments). For example, a 2023 study of university students in Nepal utilized 50 as a cut-point for severe IA and found 29.3% prevalence (Acharya et al., 2023). Such findings emphasize two underlying matters: firstly, that certain groups are put at increased risk; secondly, that inhomogeneous scoring standards limit cross-comparability and generalizability of results between different studies and settings.

Added to these problems is the dominant role of IA in the official psychiatric classificatory systems. Neither the Diagnostic and Statistical Manual of Mental Disorders (DSM-5) nor the International Classification of Diseases (ICD-11) recognizes Internet Addiction as a standalone clinical diagnosis. Although Gaming Disorder, which is commonly seen as a subtype of IA, has been included in the ICD-11, the broader category of IA remains excluded (Harrison et al., 2021). Such patchy recognition generates diagnostic inconsistency since clinicians typically end up using tentative criteria, adapted screening tools, or those established only within a given cultural or demographic context. Standardization restriction not only limits the extent of clinical assessment but also affects development of large-scale interventions.

This uncertainty of diagnosis also slows down early identification and standardization of treatment strategies. Absent definitive diagnostic criteria, clinicians will tend to underdiagnose or ascribe IA, particularly when its symptoms overlap with other conditions such as depression or ADHD. Symptom overlap, i.e., sleep disturbances, inattention, and social withdrawal, can result in confusion in clinical presentations. It can conceal the prevalence of IA as a single or primary problem (Ko et al., 2012). Additionally, cultural attitudes towards technology can also determine cultural norms regarding sensitive use of screens and varying levels of digital literacy, further complicating the matter. What is problematic in a culture can be normalized or even strengthened in another culture, thus making it even more challenging to create universal diagnostic criteria.

As prevalence increases and growing evidence for the clinical relevance of IA, there is an urgent need worldwide for an internationally agreed-on, multidimensional system of diagnosis. Such a measurement must go beyond symptom checklist in the superficial, and must incorporate comprehensive evaluations of patterns of use, functional impairment, and common comorbidities. Notably, it would have to incorporate qualitative as well as quantitative measurement instruments that are responsive to age, to cultural background, and to the ever-evolving horizon of digital technology. A standardized but adaptable diagnostic system

would not only allow for better detection and monitoring of IA, but also set the stage for more effective prevention and treatment strategies across different groups.

Table 2: Diagnostic Instruments for Internet Addiction

Instrument	Description	Items	Scoring Range	Notes
Internet Addiction Test (IAT)	Most widely used scale	20	20–100	Cut-off scores vary widely
CIAS-R	Chinese Internet Addiction Scale	26	Varies	Culturally validated in Asia
IGDS9-SF	Gaming-specific, DSM-based	9	9–45	Aligned with DSM-5 appendix

Cognitive and Neurobiological Mechanisms

Empirical investigations of Internet Addiction have primarily concerned themselves with behavioral traits and environmental influences, while relatively fewer studies have explored its cognitive and neurobiological processes. However, recent advances in cognitive neuroscience have begun to shed some light on the possible effect of IA on brain function and cognitive processing like other traditional substance addictions. Although IA is not the use of a chemical drug, it does have behavioral symptoms in common with substance use disorders: psychological craving, withdrawal, salience, and tolerance. It remains to be seen if IA also has the same psychological and physiological basis as substance addiction (Brand et al., 2019).

Cognitive neuroscience has provided scientists with helpful measures such as event-related potentials (ERPs), functional magnetic resonance imaging (fMRI), and behavioral paradigms. These measures show promise in investigating impairments in attention, memory, inhibition, and decision-making caused by IA. Studies on ERP components such as P300 and N400 have found that IA individuals, particularly those who are online gaming addicted, exhibit lower cognitive processing capacity. For example, lower amplitude and latency for P300 have been found universally, showing lower allocation of attention and delayed information processing (Dong et al., 2012). Likewise, lower amplitude and higher latency of N400 in IA participants show lower language fluency and semantic integration (Kwon et al., 2024).

In social cognition, research using ERP has shown that adolescents with IA exhibit abnormalities in recognizing facial expressions and early visual processing, which are responsible for some of their social issues (He et al., 2017). Other research has found decreased short-term memory, reasoning ability, and executive function in persons with IA (Liu et al., 2017). Complexity in resting-state EEG has been shown to be decreased in persons with IA, reflecting reduced overall cognitive engagement and mental flexibility.

Decision-making deficits are also noted. People with IA prefer immediate rewards to future negative consequences, a trait seen in substance abuse behavior. Disrupted decision-making is also noted in gambling task studies where those with IA respond more slowly to considering options and a preference for immediate reward. Neuroimaging studies confirm the same by noticing reduced activity in the prefrontal cortex and alterations in activity in the brain's reward system.

Furthermore, IA individuals demonstrate attentional bias in reacting to emotional and environmental stimuli. They devote more attentional resources to internet-related stimuli and are less reactive to positive or neutral stimuli. This attentional bias is postulated to enhance craving and chronic use of the internet, similar to cue-reactivity found in substance dependence. ERP assessments indicate enhanced P200 and P300 amplitudes to images of online gaming, indicating initial and sustained attention to addicting content (Liu et al., 2017).

Inhibition and self-control impairments in IA are also supported by Go/No-Go and Stroop paradigms, where IA users exhibit reduced inhibitory control and greater difficulty in disregarding distracting stimuli. fMRI research reveals hypoactivity within frontal regions responsible for impulse control, suggesting neurobiological underpinnings to their behavioral dysregulation. These impairments are especially prevalent among adolescents, whose prefrontal cortex is under development and who have greater susceptibility for sensation seeking (Zhou et al., 2011).

The reward system, one of the most significant systems of addiction neurobiology, has also been implicated in IA. Structural and functional imaging studies have shown overlapping organs in the human brain to cues that are internet related (e.g., dorsolateral prefrontal cortex; caudate nucleus; anterior cingulate cortex). Although IA generally activates portions of the same new circuitry associated with substance addictions (particularly related to craving and anticipated rewards), it is not complete overlap and only partial. For example, some central structures, including the ventral tegmental area and amygdala may have weaker or less stable activation in IA compared to substance use disorders (Turel et al., 2011). This suggests that IA may actually involve different pathways or patterns of dysregulation to a classic addiction, particularly regarding circuits related to emotion processing and motivational salience. Additionally, variability of activation patterns in the literature suggest that important individual factors may moderately influence activation (e.g., age, type of internet activity or behavior, and co-occurring psychological conditions). Future research will need to discern whether differences in activation reflect a fundamentally different subtype of addiction or a spectrum of behavioral addiction with distinct neural signatures.

Comorbidities

Internet Addiction typically co-occurs with several psychiatric and psychological disorders. This often complicates diagnosis and treatment. The comorbidities are often not only a function of IA, but may also contribute to the onset or continued use of the internet. The empirical research indicates that IA rarely occurs on its own; it frequently co-occurs with mood disorders, behavioral regulation difficulties and substance abuse. Anxiety and depression are very common psychiatric comorbidities and in general demonstrate a strong and consistent correlation with compulsive internet use. Individuals who suffer from either of these conditions may seek the internet as a solution to avoiding emotional discomfort, distraction from reality, or as a means of self-medicating. This frequently creates a reinforcing loop in which the positive reinforcement of temporary emotional relief encourages compulsive internet use, which in turn

further solidifies both IA and the comorbid psychological disorder (Cheng & Li, 2014; Kuss & Griffiths, 2015).

A Nepalese study of a youth population found 4.9% of individuals with IA had depressive symptoms, while 29.4% of this population had high perceived stress levels (Acharya et al., 2023). These mental health challenges created reliance on maladaptive coping methods, ultimately decreasing the likelihood that the individual will change their maladaptive internet use, or even reduce their characteristics of maladaptive use. This reinforces the need for integrative assessments and treatment processes that address all forms of internet behaviors, as well as the emotional and psychiatric conditions that tend to accompany them.

Attention-deficit/hyperactivity disorder (ADHD) is yet another strongly documented comorbid condition. IA and ADHD share similar characteristics such as impulsivity, difficulty with self-regulation, and inattention and are therefore extremely difficult to distinguish within the clinical setting. The tendency among individuals who have ADHD towards constant stimulation can lead to excessive use of quick-paced, highly stimulating online material such as social media updates and video games (Ko et al., 2012). This pattern of use may further reinforce maladaptive attention cycles and impulsive behaviors, creating a feedback loop that intensifies both conditions. As a result, differential diagnosis and treatment planning require careful consideration of overlapping symptoms and the potential bidirectional influence between IA and ADHD.

Low self-esteem is also prevalent among those with IA. In the same Nepal study, 29.4% of IA students reported low self-esteem, suggesting that those who do not have personal or social confidence may be more prone to crave approval or feelings of accomplishment online (Acharya et al., 2023). This is most evident in the case of social media addiction, where individuals spend hours fixated on likes, comments, and curation of digital images (Andreassen et al., 2017).

Furthermore, substance use disorders (SUDs) usually occur together with IA, especially among young adults and adolescents. IA and SUDs also both have similar patterns of dysregulation of the reward system in the brain, leading to craving, loss of control, and continuation of use despite adverse consequences. It has been established that individuals with IA can possess a higher proneness to alcohol and drug abuse and increase bad mental health and functioning outcomes (Ko et al., 2012).

The co-occurring presence of psychiatric disease severely complicates the treatment situation. Co-occurring conditions can mimic or hide IA symptoms, slowing down accurate diagnosis and weakening the effectiveness of monotherapy therapies. For example, depression or anxiety that is not diagnosed can hinder involvement in behavior-based treatments like CBT for IA. Similarly, stimulant-based ADHD medication can interact with internet usage patterns to suppress or enhance addictive behaviors. Keeping all these problems in sight, careful, multidimensional assessment is essential for effective intervention. Screening for IA must be incorporated as a routine process alongside common psychiatric disorders and integrated in treatment models addressing both the addictive disorder and the co-occurring psychological conditions simultaneously.

Table 1: Psychological Symptoms Associated with Internet Addiction

Symptom	Prevalence (%)	Symptom Type	Potential Consequences
Insomnia	26.8%	Physical	Chronic fatigue, impaired attention
Daytime drowsiness	20.0%	Physical	Poor academic/work performance
Eye fatigue	19.0%	Physical	Visual strain, headaches
High perceived stress	29.4%	Emotional	Anxiety, lowered coping capacity
Depressive symptoms	4.9%	Emotional	Mood disorders, social withdrawal
Low self-esteem	29.4%	Emotional	Overdependence on online validation

Mental Health Implications

Internet Addiction has profound and severe consequences for mental health, influencing not only emotional functioning but also cognitive processes and the control of behavior. As a behavioral disorder based on compulsive digital engagement, IA undermines basic processes of psychological functioning and may yield lasting impacts if left untreated. Among the most overt and pervasive impacts of IA is emotional dysregulation. Individuals with IA often exhibit symptoms such as irritability, anxiety, depressed mood, and emotional numbness when offline or excluded from access to the internet (Kuss et al., 2014). These emotional symptoms are likely to occur from dependence on virtual realms as coping mechanisms to repress stress, loneliness, or poor self-esteem. Chronic dependency on the internet for emotional support also erodes offline resilience and lowers motivation for problem-solving offline (Brand et al., 2019).

IA also involves severe cognitive consequences. Excessive use of the internet has been linked to reduced attention span, impaired working memory, and difficulty with persistent concentration (Dong et al., 2012). These effects are particularly concerning among teenagers and young adults, whose brains are still undergoing changes of crucial significance. The persistent mental stimulation by internet content can disrupt the ability to focus on low-stimulation but important activities such as reading or studying, and therefore poor academic performance.

From a behavioral perspective, IA is primarily responsible for avoidance behaviors that are disruptive to the functioning of a person's social, occupational, and recreational habits. Most affected patients socially avoid people opting for cyberspace, which causes a loss of socialization and interpersonal skills, and social isolation (Andreassen et al., 2017). Loss of socialization and relationships with peers can negatively affect emotional growth and development during adolescence, while adults' interpersonal avoidant strategies typically lead to work disengagement, reduced productivity, and ultimately burnout. In the more severe comprehensive case, the individual rejects all facets of their life including: school, work, or family which can lead to other forms of dependency and withdrawal.

IA also importantly affects physical health as well, which further supports psychological distress. Think about the typical experience of insomnia, disrupted sleep, and daytime sleeping. All are common manifestations of prolonged screen exposure, which is associated with disrupted circadian rhythm (Lam, 2014). Similarly, individuals with IA neglect healthy eating, exercise, and personal hygiene leading to sedentary lifestyle changes, and unhealthy risk exposures; all

adversely affect physical health. These physical health effects can reinforce negative body image, feeling tired, and low energy, which further diminishes motivation to return to face-to-face interactions with the offline world.

Together, the combined consequences of emotional, cognitive, behavioral, and physical dysfunction elevate people exhibiting IA to risk for serious psychiatric manifestations, like suicidal ideation, self-harm behavior, or substance use (Ko et al., 2012). These risks underscore the need to recognize IA not simply as a behavioral condition, but instead as a serious mental health illness deserving of diligent evaluation and treatment.

Treatment Strategies

There are several effective ways to treat Internet Addiction. It is helpful to think of the treatment of IA as a process with a concentrated, multimodal assessment approach that targets the cognitive, behavioral, emotional, and environmental dimensions of the issue. The most well-established and evidence-based approach to recovery is Cognitive Behavioral Therapy (CBT), which focuses on changing and reconstructing dysfunctional ways of thinking and behaving that are associated with excessive internet use. CBT encourages individuals to redirect towards healthier coping strategies, reclaim self-control, and have a more balanced relationship with digital technology (Young, 2007).

Recent clinical studies support the efficacy of CBT in reducing IA symptoms. One such trial demonstrated that a sample of university students reported a 37% reduction of IA symptoms after completing a course of CBT, providing confidence that it is effective and a useful form of therapy (Kim et al., 2018). Family involvement as opposed to self-guided treatment or therapy is also crucial when a substance (or internet) begins to disrupt the family interactions and communications, specifically with adolescents. Family structures can set boundaries and monitor behaviors to eliminate overuse and allow for accountability. Another study (Lee, 2024) found parental monitoring was associated with a 29% decrease in one study of youth overuse of smartphones, strengthening the importance of family relationships on treatment outcomes. Markers of effective change, like improving family communication, establishing, and setting clear digital boundaries, and involving a family member or caregiver on behavioral planning have been important behavioral change processes during recovery or treatment. Pharmacological treatment is not typically the initial treatment of IA but may be used when there are prominent psychiatric comorbidities in the form of depression, anxiety, or ADHD. There have been some initial promises with medications like SSRIs and bupropion in decreasing the symptoms of impulse control and mood regulation (Sá et al., 2023). But additional clinical trials will have to be performed before they are an integral part of IA treatment.

Behavioral interventions such as digital detox programs have become popular “short-term” treatment options. Digital detox programs endorse scheduled periods of technological abstinence, typically in the attractive setting of a retreat or school. Digital detoxing may not typically yield ongoing behavioral change unless coupled with consistent psychological treatment and cognitive reframing and restructuring. Circumstantial tools like screen-time

tracking apps, self-monitoring logs, and scheduled goal setting exercises may help make individuals more aware of their online behavior and assist in contributing to a decrease in that behavior (Turel et al., 2011).

Further, there are preventative steps to consider as a foundation for “long-term” IA prevention. Public health approach campaigns, digital literacy taught in schools, and community health outreach will be able to help put strategies in place to promote healthy use of the internet. In at-risk youth populations, preventative interventions which promote time management awareness tools and appropriate positive social interactions away from the internet, along with the promotion of mindful use of technology become more imperative. Ultimately, a comprehensive intervention to treat IA should include individual psychotherapy, family therapy, possibly targeted pharmacology, and even longer-term behavioral interventions. Along with preventative education, and policy work, together these approaches can make a difference in promoting lower individual and societal burden from IA and healthier digital lives.

Prevention and Intervention Strategies for Adolescents

Prevention and treatment of IA among teens must be multi-component, multifaceted, and cover the family, schools, and the teens themselves. Parent education and counseling must be the initial and primary step in prevention. Parents should learn to recognize how their parental style, family processes, and communication patterns affect their children's use of the internet (Wang et al., 2013). Early parental intervention in regulating internet behavior has been shown to be highly effective compared to interventions made later. For instance, a school in Guangzhou China implemented a “school-family-community” collaborative approach in order to allow parents to understand the risk of IA and how to establish good internet habits in children (Zhang et al., 2024). They did this by setting reasonable restrictions on screen time, openness in communication, and finding an even-handed approach towards online games. Parents must take the initiative to model good internet practice themselves by limiting their own screen time, especially on entertainment and gaming. They should not also use punitive approaches but instead be interested in their children's online activities in an effort to establish confidence and learn to understand one another. With the growth of children, so do their psychological needs. Thus, parents ought to work together with them in formulating functional internet-use plans that entitle self-monitoring exercises, rewards for good behavior, and counseling upon encountering obstacles.

Apart from family counseling, schools also play a significant role to prevent and intervene IA. Teachers can promote healthy internet use by incorporating digital literacy education into the curriculum. This means incorporating class lessons and workshops that outline the pros and cons of internet use. Online behavior and emotional health classes that teach mental health via role-playing, case discussion, and peer work can allow students to learn increased awareness and resilience (Livingstone et al., 2014). More offline interaction is also needed. By encouraging students to join extracurricular activities such as sports or music, schools contribute to a sense of belongingness and self-worth that can dissolve individual dependence on virtual

spaces. Regular parent-teacher meetings also need to be held to synchronize efforts at home and school. This not only monitors students' academic as well as emotional development, but it also discusses internet use at home. Parent seminars and workshops can provide parents with an awareness of the psychological mechanisms of IA and educate them on good communication skills to facilitate better parent-child relations (Chang et al., 2014).

Finally, the teens themselves must ultimately be responsible for preventing and treating IA. They must possess a positive outlook towards life and project a clear image of their aspirations. Knowing how to convert stress into motivation and build emotional strength are essential. Adolescents, when faced with emotional problems, should be encouraged and taught to express themselves constructively. Expressive writing or verbal self-talk are the therapeutic techniques by which they can reevaluate distorted thinking and improve parent-child communication. In addition, involvement in physical and social activities is a constructive release of pent-up tension and energy. Most importantly, adolescents should acquire appropriate attitudes towards the use of the internet. This entails adherence to school and national policy, staying away from dangerous content on the internet, and self-restriction. By setting strong intentions for each internet session and managing both time and content, they are able to develop a structured and healthy style of living on the internet. Therefore, Through the combination of family support, school participation, and individual responsibility, internet addiction can be stopped to a significant level and productive and balanced use of the internet guaranteed among adolescents.

Conclusion

Internet Addiction (IA) is a complex and multifaceted behavior disorder. It poses serious risks to emotional and social well-being. With the expansion of digital technologies in deepening involvement in nearly all areas of living, identification and understanding of IA have become more important within clinical and public health contexts. This paper highlights the rising and epidemic incidence of IA in youth and identifies its strong association with a range of psychiatric comorbidities as well as psychological risk factors.

Determining the most significant risk factors (impulsivity, low self-esteem, stress, and dysfunctional family histories) within the co-morbidity of conditions such as depression, anxiety, and ADHD is crucial to an understanding of which groups are most vulnerable to IA (Anderson et al., 2017; Weinstein et al., 2015). Furthermore, the diagnostic challenges presented by a lack of standardized criteria emphasize the need to guarantee consistent, evidence-based systems for the purpose of reliable identification and comparability between cultures and studies (Kuss et al., 2014).

Effective intervention for IA requires a multi-method approach that engages family, cognitive-behavioral therapy, medications when indicated and preventing education of optimal digital use (King et al., 2017; Winkler et al., 2013). There is still much to be learned. Future research needs to standardize testing measures, identify the neurobiological and cognitive mechanics of IA, and longitudinal studies on the efficacy and duration of different types of

therapeutic interventions. Both the clinical and research communities can better position individuals and societies to engage with their digital participation in ways that maintain their well-being rather than destroy it by closing the gaps in knowledge and intervention. Our environment continues to change, and so must our methods to ensure that the digital presence is one that promotes, rather than jeopardizes, mental health.

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Polygenic Risk Scores and the Problem of Precision: Socioeconomic Disparities in Genomic Risk Prediction and Modern Medicine By Joonwoo Lee

ABSTRACT

Polygenic risk scores (PRSs) predict individuals' genetic risk of developing specific medical conditions through a summative score that compares with the general population. Based on genome-wide association studies (GWAS) that identify genetic variations in human genomes correlated with disease, PRSs and their development provide promising progress in precision medicine, which emphasizes prevention and proactive intervention rather than reactive treatment. This paper synthesizes evidence from a targeted literature review and expert interviews to evaluate the promise and pitfalls of PRS in modern medicine, with a focus on socioeconomic and ancestry-related disparities. The study outlines ethical, legal, and social risks—including ancestry bias from Eurocentric GWAS, privacy and insurance concerns, genetic determinism, and uneven access to testing and counseling. The study analyzed health system prerequisites for responsible deployment, emphasizing the integration of PRS with electronic health records, standardized data models, clear communication and consent practices, and workforce training. Structural barriers, such as limited diversity in genomic data and fragmented EHR infrastructure, prevent widespread implementation of PRS. The findings and expert testimonies suggest that PRS should complement, rather than replace, established risk factors—clinical, behavioral, and social. In addition, the equitable translation of PRS requires diverse cohorts, transparent reporting of ancestry-specific performance, genetic counseling, and safeguards against insurer bias. With proper policy guardrails, PRS can shift healthcare from reactive treatment to proactive prevention, which allows for a better health outcome future.

Keywords

Polygenic Risk Scores, Precision Medicine, Genomic Medicine

INTRODUCTION

Genetic factors that influence an individual's phenotypes, including medical conditions and diseases, are categorized into two broad categories of genetic variations: single variations of large effect and numerous small-impact variations across entire genomes. Research and clinical efforts for Mendelian disorders caused by large-effect single variations have seen significant progress, with researchers identifying crucial large-effect variations in genomes associated with the corresponding phenotypes. However, the phenotypes of many common disorders are influenced by numerous small-impact variations across the entire genome, all of which contribute to an individual's risk of expressing the unfavorable phenotype.

Genome-wide Association Studies (GWAS) are designed to identify genetic variants responsible for complex phenotypes at various loci throughout the genome. By examining large samples of individuals' entire genomes, GWAS identifies common points of genetic variation in the genomes that are statistically associated with the phenotype, which often involves diseases.

GWAS is most significantly used for identifying associations between single-nucleotide polymorphisms (SNPs) and common diseases with genetic influences, such as heart disease and diabetes¹. Projects and organizations such as the Human Genome Project, the SNP Consortium, and the International HapMap Project have worked towards identifying millions of common DNA variants, which were primarily SNPs². For psychological conditions, including autism spectrum disorder³, bipolar disorder⁴, attention-deficit hyperactivity disorder⁵, and schizophrenia⁶, GWAS identified genetic loci for different conditions overlapping one another, suggesting a relevant association between these conditions and revealing implications regarding their genetic and biological architectures.

With genetic testing becoming increasingly available for clinical use, researchers developed models based on GWAS to predict an individual's genetic risk level of developing conditions or diseases. Polygenic Risk Scores (PRS) are metrics based on GWAS that predict and summarize an individual's genetic risk of particular polygenic diseases. By summing SNPs with appropriate weights identified by GWAS depending on their effect size, PRS quantifies an individual's genetic risk in a score that is comparable to the general population in a normal distribution. Such tools could assist healthcare experts and patients in diagnosis and early prevention by providing summaries of genetic susceptibility for certain conditions, similar to the usage of family history in the diagnosis and prevention of Mendelian diseases.

However, problems and inaccuracies in the clinical implementations of PRS arise due to the makeup of samples used to conduct GWAS. Due to various limiting factors, including accessibility for sampling, GWAS often fails to accurately represent populations of non-European descent, which consequently impacts PRS accuracy and effectiveness in such populations, as PRS accuracy weakens with increasing genetic distance from the initial study cohort. For example, in a study that presented polygenic prediction for schizophrenia, statistically significant differences between scores of those who developed and did not develop the condition only existed for individuals of European ancestry⁶. Prior studies have also indicated that such inaccuracies are especially exaggerated in African ancestry groups over other non-European ancestry groups⁷. Moreover, PRS performance differs by other demographic factors, including socioeconomic status, sex, and age, implying further complications even within the same ancestry groups^{8,9}.

Linkage Disequilibrium (LD), the non-random association of alleles at different loci, plays a critical role in polygenic risk prediction, especially in the context of diverse ancestry groups. Various factors, including genetic drift, selection, demographic factors, variable rates of mutation, recombination, and gene conversion, shape LD and its patterns. LD patterns are crucial in association studies that aim to map the genome responsible for medical conditions, and consequently, predictive tools such as PRS. Due to the relationship between population history and LD, its patterns tend to vary among populations of different ancestry groups. Therefore, LD patterns must be thoroughly considered across diverse ancestry groups in identifying SNPs and constructing polygenic risk assessment models.

METHODOLOGY

The research process involved a literature review with validation through expert interviews. To identify relevant studies for this review, a literature search was conducted across PubMed and Google Scholar with search terms including a combination of the following keywords: “polygenic risk score”, “PRS”, “genome-wide association study”, “GWAS”, “ancestry bias”, “genetic determinism”, “ELSI” (Ethical, Legal, and Social Implications), and “EHR integration.” After an initial search for sources discussing fundamental concepts of genome-wide association studies, polygenic risk scores, single-nucleotide polymorphism, and linkage disequilibrium, specific themes, including ethical, legal, and social implications, novel statistical methods, electronic medical record implementation, and other existing research were explored. To further discuss the implications and significance, potential benefits of PRS, challenges and limitations of PRS, global cooperation efforts, and future directions of research, a mixed-methods approach was employed, incorporating expert insights into specific topics gathered through virtual interviews.

RESULTS

Ethical, Legal, and Social Implications

Considering the potential disparities caused by various factors, including but not limited to differences in ancestry groups and socioeconomic status, researchers examined the equitable adoption of polygenic prediction in clinical settings. For the ethical research of genomic science, researchers established an international framework that considers ethical, legal, and social implications (ELSI). Aimed at accelerating the translation of ELSI findings into practice and policy, frameworks such as ELSI 2.0 enable ELSI research to effectively respond to emerging developments with global collaboration by examining the impact of research¹⁰. Based on such frameworks, researchers considered guidelines for the ethical implementation of precision genomic medicine.

Despite these efforts, the equitable use of polygenic risk scores (PRS) remains a contentious topic across bioinformatics, bioethics, and public health. Despite its leadership in genomic research, the United States exhibits more severe health outcomes than in other high- and middle-income countries¹¹, underscoring the urgency of equitable implementation. Accessibility challenges such as language barriers, limited infrastructure and socioeconomic constraints persist among minority groups, and the extent to which current PRS models can mitigate these existing inequities remains uncertain. Researchers have also criticized potential issues with the reporting and interpretation of PRS results, expressing concern regarding overdiagnosis and overtreatment¹², violation of privacy¹³, psychological harm to pediatric patients¹⁴, misinterpretation of results in a stigmatizing or discriminatory manner^{15, 16}, and more.

One of the most significant concerns regarding the application of PRS in clinical settings is the potential discrimination based on ancestry, race, ethnicity, and genetics. The issue of inaccurate representation of non-European individuals persists in most current models, raising

significant concerns about health disparities. The association of health conditions with genetics may also exacerbate systemic racism and existing health inequities, as an obsessive focus on genetics may encourage policymakers to ignore relevant causes of health disparities among different racial groups. Without relevant contexts, the consideration of polygenic risk prediction may lead to misleading interpretations, particularly in understanding a population's likelihood of developing certain conditions. Moreover, pediatric and prenatal testing may also enable eugenics when results are interpreted with an unethical emphasis on genetics. Genetics is not the sole factor that determines an individual's likelihood of developing health conditions, as a complex combination of circumstances, including but not limited to social determinants of health (SDOH), gene-environment interactions (GxE), and lifestyle choices, contributes to the risk. Acknowledging the role of non-genetic factors in disease is crucial, as genetic determinism, the idea that overemphasizes the role of genes in forming traits, can enable discriminatory beliefs and prejudice, healthcare disparities, and unhealthy lifestyle choices based on inappropriate assurance. In an analysis of associations of self-reported race, SDOH, and PRS with coronary heart disease (CHD), a study found that SDOH and PRS had independent associations with CHD¹⁷.

Insurance-related implications are another major area of concern. Highly predictive genetic tests could lead to discriminatory pricing practices. While legislation such as the Genetic Information Nondiscrimination Act of 2008 (GINA) in the United States and the Genetic Non-Discrimination Act in Canada, prevent the use of genetic information to set insurance pricing¹⁸, significant policy gaps remain. GINA, for instance, fails to address critical aspects of risk prediction, such as long-term care, disability insurance¹⁴, and life insurance¹⁸. In Australia, industry self-regulation provides only partial protection. Such gaps may discourage individuals and instill fear in individuals undergoing genetic testing due to fear of discrimination, further exacerbating health disparities. Ensuring the equitable application of PRS in clinical settings requires the cooperation of experts from disciplines, including but not limited to bioinformatics, bioethics, social psychology, public health, and policymaking.

Advances Current PRS Research

To address the difference in predictability between ancestry groups, researchers have developed novel statistical methods that enhance PRS accuracy and transferability. These methods include clumping/pruning, and thresholding (C+T or P+T), Bayesian regression models using continuous shrinkage priors (PRS-CS and PRS-CSx), elastic net penalized regression ensemble models (PRSMix, PRSMix+, PROSPER), multi-ancestry GWAS-derived PRS (PRSmulti), and many more. P+T involves selecting, filtering, and grouping SNPs based on p-value thresholds, heuristically accounting for LD patterns of different ancestry groups¹⁹. Bayesian regression models with continuous shrinkage (CS) priors infer SNP effect sizes using GWAS summaries and external LD reference panels^{20, 21}. Elastic net penalized regression ensemble models combine existing PRS models, such as those in the PGS catalog, an open

database of published PRS models^{22, 23}. Other studies also built upon a meta-analysis of multiple single-ancestry group GWAS to create a multi-ancestry GWAS for increased accuracy in PRS¹⁹.

Researchers used tools such as phenome-wide association studies (PheWAS), which analyze an SNP or other genetic variants across various phenotypes to explore gene-disease associations, to transfer existing PRS models to different ancestry groups¹² and identify the shared genetic etiology between Alzheimer's Disease (AD) and other conditions, where researchers observed strong associations between AD PRS and mild cognitive impairment, memory loss, and dementias, which are AD-related phenotypes²⁴. Moreover, to address the shortcomings of GWAS and PRS in admixed populations, researchers incorporated tools such as Tractor and Ancestry-Based Weighted Dosage Score (AWDS) to account for individuals of admixed ancestry. Tractor is used to develop local ancestry-informed GWAS that include admixed individuals¹⁹, while AWDS²⁵ expands on previously developed Weighted Haplotype and Imputation-Based Tests (WHaIT) that identify associations of rare variants to better account for admixed individuals²⁶.

As commonly discussed in ELSI research, PRS only considers the genetic aspect of disease risk, which also involves lifestyle choices, SDOH, GxE, and more. Although PRS is valuable in that it can identify substantially larger fractions of the population at high disease risk than monogenic mutations, it must be considered as an addition to currently considered disease risk, including but not limited to clinical factors, biochemistry, lifestyle, and family history, rather than a replacement. Researchers have developed methods to consider contexts relevant to health outcomes, including frameworks such as CalPred, which calibrates PRS in the context of health conditions such as age, sex, and body-mass index; socioeconomic factors such as annual household income and education attainment; and lifestyle choices such as smoking status, alcohol consumption, and years at current address²⁷. In a study that expanded screening eligibility for breast cancer, researchers incorporated traditional risk factors such as demographics, reproductive history, menopausal status, family history, previous biopsies, and mammographic density along with PRS to account for non-polygenic risk factors²⁸. Researchers of the Electronic Medical Records and Genomics (eMERGE) Network also continue to address bias in genomics research, including individuals with consideration of income, minority ancestry groups, disabilities, and more in their samples¹¹.

Moreover, there have been increasing efforts to improve PRS accuracy by diversifying data collection. For example, collaborations between the Uganda Virus Research Institute and the University of Cambridge and Sanger Institute enabled the development of the Uganda Genome Resource, the largest published genomic study of continental Africans to date. Similarly, international efforts in regions including South Asia, Latin America, Australia, and Asia have increased sample diversity for genomic data. Institutions and alliances, such as UGR, the Pakistan Alliance on genetic Risk factors for Health (PARKH), the Latin American Genomics Consortium, and the National Centre for Indigenous Genomics in Australia, have successfully increased sample diversity through effective cooperation, resource allocation, and agreements with underrepresented indigenous peoples²⁹.

Clinical Application of PRS

There exist distinct categories of PRS utility: informed therapeutic intervention, informed disease screening, and informed life planning. In PRS-informed therapeutic intervention, researchers have examined the effectiveness of identifying high-risk individuals to provide treatments. For preeclampsia and eclampsia, a rare pregnancy complication in which low-dose aspirin is used as a preventative measure, a PRS model was able to expand aspirin eligibility, capturing more individuals who developed the condition³⁰. For CHD, PRS models identified individuals who would greatly benefit from statin dosages, providing an effective solution to the current model of providing low to medium dosages of statins for individuals between the ages of 40 and 75 who have at least one risk factor for an adverse cardiovascular event, including obesity, diabetes mellitus, high blood pressure, and smoking^{31, 32}. PRS can also help identify individuals who would benefit from additional disease screenings, especially for cancer. For breast cancer, PRS results identified individuals at high risk, demonstrating potential to assist clinicians in deciding to initiate screening earlier than the standard age of 50^{28, 32}. PRS can also enable appropriate life planning—results can aid clinicians in encouraging behavior change in patients and clients, as the results clarify their susceptibility to diseases. Moreover, organizations and corporations such as 23andMe and Impute.me have developed Direct-to-Consumer (DTC) testing, which can enable insightful conversations between physicians and patients with proper education³¹.

Considering the benefits of PRS in clinical practice, researchers have worked towards implementing polygenic risk prediction as a part of electronic medical records (EMR). First implemented in the Regenstrief Institute in 1972, EMR serves as a singular, centralized data source with relevant information, including billing information, laboratory results, patient demographics, surgical codes, family history, and more¹³. Lack of environmental context is a critical issue in genomic precision medicine, which includes PRS, and improving existing EMR infrastructure to contain structured and consistent data can greatly accelerate progress on genomic medicine studies through participant-imputed GWAS data. Research efforts have attempted to enable the coherent integration of genetic testing results in EMRs by addressing accessibility issues, such as storing testing results as non-searchable PDFs, that hinder data analysis and coordination³³.

The Electronic Medical Records and Genomics (eMERGE) Network, a national network organized and funded by the National Human Genome Research Institute for the implementation of genomic medicine, leads the clinical implementation of PRS with EMR³⁴. In the eMERGE Network, researchers have conducted ELSI research for returning electronic medical records containing PRS results, making decisions regarding critical issues such as the grouping of individuals based on ancestry, the use of group-specific metrics, the choice of terminology for validation groups, the choice of disclosed information, the choice of wording for high and low risk, and more⁸. Based on research regarding the return of genomic test results to patients, the eMERGE Network developed the Genome-Informed Risk Assessment (GIRA) as part of Phase IV of the network, compiling risk information from polygenic, monogenic, family history, and

clinical factors. GIRA was incorporated into individuals' medical records and returned to both individuals and their healthcare providers, which included study staff members, study physicians, and site genetic counselors trained to describe results of risk assessments and future steps to patients³⁵. In the development process of GIRA, researchers considered patients' knowledge, harm by worry and harm by false reassurance, cohort-appropriate education, improving genomic knowledge of providers, communicating program goals and implications to providers, clinical decision support (CDS), and more¹¹. Concluding that the incorporation of genomic risk information could improve risk management, the eMERGE network gathered samples and selected PRS models for clinical implementation, considering several selection criteria, including condition prevalence, strength of evidence for performance, clinical expertise, and data availability for validation in diverse populations. Although the network processed 2,500 participants through the clinical PRS software pipeline between July 2022 and May 2023, the researchers identified existing limitations, such as the healthcare providers' and patients' understanding of PRS, the potential for the emergence of genetic determinism, and the lack of disease prevention strategies after the return of results³⁶.

While integrating PRS results in electronic records, data from existing health records are used to develop, improve, validate, and calibrate polygenic prediction models. Unlike recruiting for samples from a broader population, incorporating electronic health record (EHR) data enables efficient longitudinal studies and clear control groups, and EHR-based PRS models can be continually validated and calibrated with updated patient information. Traditional validation methods for PRS involve separate and independent GWAS data, which may include inconsistencies with the original GWAS used to develop the PRS, while EHR-generated PRSs can be continually evaluated on new patients, who are accurately representative of the original cohort. Moreover, EHR data are more representative of local healthcare system populations than traditional GWAS data. The Global Biobank Meta-analysis Initiative (GBMI) is a collaborative network of 23 biobanks across four continents, representing more than 2.2 million participants with genetic data linked to EMRs, enabling the integration of GWASs in biobanks worldwide³⁷, and Global Biobank analysis indicated that PRS accuracy also benefited from increased diversity enabled by EHR integration³⁸.

DISCUSSION

Overview

Despite PRS's considerable potential to improve individual health outcomes and reduce overall healthcare expenditures, polygenic risk scores (PRS) present a complex array of ethical, legal, and social considerations that must be addressed before widespread clinical adoption. Key challenges include ancestry bias in GWAS datasets, potential misuse of genetic data by insurers and public institutions, insufficient data infrastructure, possible psychological harm to patients, and the risk of exacerbating existing health inequities. Addressing these concerns requires robust guidelines, protective legislation, and interdisciplinary collaboration. This discussion examines

the potential benefits of PRS, challenges in interpreting results and communicating findings, key limitations in current research and implementation, and future directions for clinical and scientific advancement.

Potential Benefits of PRS

The greatest potential of polygenic risk prediction and genomic precision medicine lies in the emergence of proactive, preventative medical practices. As described previously, researchers found significant utility for PRS as a tool to initiate preventative treatment, additional screening, and lifestyle interventions. In diseases with considerable environmental factors, such as CHD, appropriate lifestyle choices can greatly benefit individuals with high genetic risk. Additionally, in the case of conditions with screening tests that have high false-positive rates, such as prostate cancer, PRS can also aid in the interpretation of screening results. The United States Preventive Services Task Force currently recommends against prostate-specific antigen screening due to the adverse effects of false positives and an undesirable risk-to-benefit ratio. However, a prostate cancer PRS can identify individuals with high genetic risk, and such individuals have a greater risk-to-benefit ratio than the general population³².

Healthcare in the United States has mostly focused on reactive care and treatment. With highly predictive risk assessment tools such as PRS, preventative strategies can drastically improve individual health while decreasing healthcare expenditures. Dr. Niall Lennon, senior director of the genomics platform at the Broad Institute of MIT and Harvard and the eMERGE Network, claimed that well-validated and robust disease risk assessment tools, including but not limited to polygenic risk, could significantly reduce disease burden, morbidity, and mortality, reducing overall healthcare spending. He discussed the status quo of U.S. healthcare and its costly disease treatment, and how the incorporation of disease risk information in healthcare could not only reduce spending but also improve individual health. Even for individuals who are already aware of other risk factors, genetic risk prediction can quantify the potential of developing conditions. Dr. Ying Wang, researcher and instructor at Massachusetts General Hospital, Harvard Medical School, and the Broad Institute, also claimed that PRS has the greatest potential in risk stratification and improving early detection and prevention for common, treatable conditions in the general population. For conditions such as CHD, where clinical and lifestyle interventions or population screening are available, polygenic risk prediction can initiate screening and intervention in high-risk individuals while reducing unnecessary screening in low-risk individuals.

Interpretation and Communication of PRS Results

The ethical and equitable use of PRS hinges on how results are interpreted and communicated to patients. Clear communication — including the selection of which results to disclose, the language used, and the context provided — is essential to prevent misunderstanding and potential harm. Informed consent plays a critical role, as genetic risk disclosure may inadvertently reveal sensitive familial or ancestral information.

Psychological impacts are another key concern. Patients informed of elevated genetic risk may experience anxiety, paranoia, fatalism, or hypochondria. This risk is heightened by the public's limited understanding of genomic medicine and the probabilistic nature of PRS. As Dr. Yunfeng Ruan of the Broad Institute emphasizes, patients must be educated about the meaning and limitations of PRS, including the fact that these scores are correlative, not causal. Dr. Lennon underscores that “genetics is not destiny,” and advocates for communicating results in more intuitive terms — such as five-year absolute risk — rather than abstract polygenic scores.

Regarding the potential psychological harm to patients, Dr. Ruan clarified that the communication of results is discussed in the methodology for the research, deciding whether or not to inform clients of their polygenic risk information for an earlier diagnosis or to avoid psychological harm. Dr. Lennon provided similar insight, stating that the eMERGE Network considered actionability and consent in the process of determining the communication of PRS results. Both Dr. Ruan and Dr. Lennon identified consent as a critical aspect of PRS communication, as patients may wish to avoid the psychological burden of being informed of polygenic risk. Dr. Wang also stated that, to mitigate potential psychological harm—paranoia, fatalism, or hypochondria—results should be communicated by trained professionals, embedded in genetic counseling, and paired with actionable recommendations rather than stand-alone risk scores. Such measures are especially crucial for conditions with limited treatment options, such as schizophrenia or Alzheimer's disease, where the benefits of communicating PRS are less clear.

Challenges and Limitations of PRS

Because PRS and genomic precision medicine are relatively new, education for both clinicians and the public remains a major challenge. Healthcare providers must learn how to interpret polygenic data, explain results clearly, and place genetic risk in a broader clinical context to avoid genetic determinism. Continuing Medical Education (CME) programs should include PRS and genomic tools as standard coursework. Communication must also be inclusive — using multiple languages, clear visuals, and accessible explanations — to ensure patients of all backgrounds understand their results. Alternative delivery methods, such as video calls, secure online platforms, or confidential letters, can further improve access to genetic risk information.

A lack of participation from minority groups in genomic research remains one of the largest obstacles. Distrust — often driven by concerns about privacy violations and misuse of genetic data — discourages participation and deepens disparities. Building trust is essential. Endorsements from medical societies, transparent data policies, and dedicated outreach staff who can explain how participation reduces health disparities are effective strategies.

Experts emphasize that overreliance on European data is a key limitation. Models built primarily on European populations perform unevenly across other groups, which could worsen inequities if not addressed. Public communication must emphasize that disease risk is

multifactorial, shaped by genetics, family history, environment, and lifestyle. Risk should always be presented as part of this broader picture.

All interviewed researchers emphasized the importance of diverse samples. Dr. Wang noted that overrepresentation of European ancestry stems from historical investments and unequal infrastructure. Representative datasets that account for ancestry, socioeconomic status, age, sex, and environment are essential for accurate validation. As Dr. Ruan described, data are the “raw materials,” while statistical methods are the “cooking skills” needed to produce reliable results. Programs like All of Us try to address this by offering benefits such as free clinical results and compensation to participants. Dr. Ruan emphasized that collecting diverse data benefits not only underrepresented groups but also improves public health overall. Clearly explaining these benefits and addressing privacy concerns can encourage greater participation.

Another challenge of PRS development is the decentralization of data, especially for EHRs, as only a minority of electronic record systems incorporate patient genetic information¹⁶. This hinders progress in EHR-based PRS development and also raises concern regarding the exacerbation of existing health disparities, as only certain cohorts may be represented in EHR-based studies. EHR infrastructure must be developed in a centralized manner with consideration of existing disparities to enable equitable access and research in genomic precision medicine.

The current state of funding in the United States presents one of the most significant challenges in PRS research. Under the 21st Century Cures Act enacted in 2016, the National Institute of Health’s All of Us Research Program is funded by the U.S. government. However, beginning in the 2024 fiscal year, there have been significant reductions to this budget—\$184 million in 2024 and \$199 million in 2025⁴⁰. The Broad Institute is one of All of Us’s genome centers responsible for genotyping and genome sequencing with an aspiration to reach one million individuals’ worth of data, and according to Dr. Lennon, this progress has since slowed due to the shutdown of recruitment centers associated with funding cuts. Dr. Ruan agreed, claiming that the decrease in research budget presents a threat to collecting diverse samples. Similarly, Dr. Wang stated that funding cuts risk exacerbating inequities, as All of Us is one of the few large-scale efforts prioritizing diverse representation. The reduction in budget has also directly impacted her research, as it limits access to large minority cohorts used in multi-ancestry methods development and applications.

Not all PRS models are ready for clinical use. Their usefulness depends on disease characteristics and available interventions. For conditions like Alzheimer’s disease, where treatments are limited, the value of disclosing polygenic risk is uncertain. PRS should not replace traditional diagnostic tools but instead complement clinical factors, biochemical markers, lifestyle data, and family history. While PRS can support the interpretation of other screening results, it remains a predictive tool — not a diagnostic one.

Overall, PRS and genomic precision medicine are still in early stages. Continued validation, larger and more diverse datasets, improved infrastructure, and sustained funding are necessary for their equitable and effective integration into healthcare.

Future Directions of PRS Research and Application

While previous initiatives, such as the Precision Medicine Initiative and the 21st Century Cures Act, attempted to increase research necessary for the implementation of genomic and precision medicine, continued support of existing initiatives and new legislative action must be prioritized. Especially in the United States, Dr. Lennon stated, insurance is closely linked to employment, and there exist potential concerns that insurance companies may make unfavorable decisions toward individuals. Associated insurance complications may lead individuals to forgo taking advantage of genetic testing, and policies need to provide protective measures similar to those in GINA. Dr. Wang agreed, advocating for legislation that safeguards against genetic discrimination, ensures equitable access to testing, and prevents stigmatization. She added by stating that guidelines should also mandate the transparency of PRS performance by ancestry group before clinical use.

A future direction in PRS research is to continue integration with EMR in both clinical and research settings. Including genome sequence data in electronic clinical records can improve data access for both research and population health insight. The Global Biobank Meta-analysis Initiative (GBMI) was developed on the basis that genetic discovery benefits from EMR-linked biobanks, despite differences among biobanks and their cohorts³⁷. Moreover, larger sample sizes and greater diversity of GBMI improved PRS accuracy³⁸.

International efforts can significantly reduce existing disparities, as demonstrated by previous initiatives in Africa, South Asia, and Australia. Dr. Lennon emphasized global cooperation as a core concept of major research programs, such as the UK Biobank and All of Us, which are accessible to researchers worldwide. Dr. Ruan claimed that there are significant benefits to global cooperation, as it provides insight into GxE in samples and will lead to efficient research through coordinated efforts. While acknowledging the benefits of global cooperation in improving the predictive powers and generalizability of PRSs, Dr. Wang also emphasized the necessity of harmonized data standards, privacy-preserving federated analyses, and international governance frameworks that balance data protection with scientific progress.

According to Dr. Lennon, the eMERGE Network's Phase IV studies have focused on the initial launch and implementation of PRS, and future research will lie in analyzing the outcomes of implementation to progress in widening the clinical adoption of polygenic risk tools. Dr. Ruan discussed advancements in understanding the population and environmental context, fine-mapping, and other research as potential directions for future research to delve deeper into genetic information. Dr. Wang identified moving towards integrating longitudinal EHRs, socio-environmental factors, genetics, and other -omics data for developing dynamic risk prediction models as a direction of future research.

CONCLUSION

This study evaluated the promises and pitfalls of PRS in modern medicine—although PRS enables the shift of healthcare towards proactive prevention, its clinical adoption is currently limited by ethical and practical challenges. Most notably, the reliance on Eurocentric

data for PRS construction leads to the disparity in accuracy and predictability between individuals of different ancestry groups. Ethical, legal, and social implications, such as privacy and insurance concerns, genetic determinism, and inequitable access, must also be considered not only in the development but also in the implementation of PRS. To enable the equitable and pragmatic adoption of PRS into existing healthcare systems, key legislation similar to GINA must provide rigid guardrails and protection, ensuring that the issues of privacy, insurance, ancestry bias, genetic determinism, and inequitable access do not hinder the practice of precision medicine or exacerbate existing health disparities. Policies, while addressing disparities and concerns, must also foster the continuation of genomic research that enables precision medicine, providing sufficient funding for infrastructure, recruitment, validation, and implementation studies, as such are the fundamental necessities to address existing shortcomings of PRS and its adoption. Crucial research goals, such as diversifying samples and integrating genomic medicine in EHRs, are in introductory stages and require national-level funding for the centralization of research efforts. Moreover, campaigns must be organized to educate the public about genetic testing and precision medicine, while reducing stigmatization or misconceptions regarding emerging genomic medical tools.

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APPENDIX

Abbreviations

1. PRS: Polygenic Risk Score

2. GWAS: Genome-Wide Association Studies
3. SNP: Single-Nucleotide Polymorphism
4. LD: Linkage Disequilibrium
5. ELSI: Ethical, Legal, and Social Implications
6. SDOH: Social Determinants of Health
7. GxE: Gene-Environment Interaction
8. CHD: Coronary Heart Disease
9. GINA: Genetic Information Nondiscrimination Act of 2008
10. C+T/P+T: Clumping/Pruning and Thresholding
11. CS: Continuous Shrinkage
12. PheWAS: Phenome-Wide Association Studies
13. AD: Alzheimer's Disease
14. AWDS: Ancestry-Based Weighted Dosage Score
15. WHaIT: Weighted Haplotype and Imputation-Based Tests
16. eMERGE: Electronic Medical Records and Genomics (Network)
17. PARKH: Pakistan Alliance on genetic Risk factors for Health
18. EMR: Electronic Medical Record
19. EHR: Electronic Health Record
20. DTC: Direct-to-Consumer (Testing)
21. GIRA: Genome-Informed Risk Assessment
22. CDS: Clinical Decision Support
23. GBMI: Global Biobank Meta-analysis Initiative

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Frontiers In Window Technology: A Comparative Analysis of Smart Glazings for Energy-Efficient Buildings By Bryan Woo

Abstract

Smart window technology is emerging and has the potential to revolutionize energy-efficient buildings. In 2024, heating, ventilation, and air conditioning systems are estimated to have contributed to over 25% of global carbon dioxide emissions, highlighting the urgent need for sustainable architectural innovations. Windows are key components to target thermal comfort energy use because their configuration regulates solar radiation. We analyze the structure and performance of five smart window technologies: electrochromic, thermochromic, suspended particle device, polymer-dispersed liquid crystal, and micro-blind windows, and test their properties using a daylight bulb and spectroradiometer to determine light transmittance ratios. Their ability to dynamically change the solar heat gain coefficient and visible light transmittance ratio expands upon traditional windows, where these metrics are static. We conclude based on experimental measurements of the solar heat gain coefficient and visible light transmittance that both suspended particle device windows and/or micro-blind windows are optimal in climates with high seasonal variability and frequently hot summers, while polymer-dispersed liquid crystal windows have the advantage of extra privacy without sacrificing costs to heat. Our final recommendation is based on the yearly average temperatures of a region: above 18 °C should install SPD or micro-blind windows because they block the most solar radiation at 94% and 96%, respectively; between 6 °C and 18 °C should install electrochromic or thermochromic because they are cost-effective; and below 6 °C should install PDLC or traditional windows.

1. Introduction

Greenhouse gas emissions from human energy production have contributed to melting ice sheets, acidifying oceans, and increasing global average temperatures (Davis, 2010). Energy consumption from heating, ventilation, and air conditioning (HVAC) in buildings accounts for more energy use than industry and transportation combined (Amasyali, 2018). Considering all emission factors, HVAC is estimated to account for 25% of global CO₂ emissions (González-Torres, 2022). Therefore, along with sustainable energy generation methods, solving the root issue of interior climatization energy consumption is critical to battling climate change (Granqvist, 2014).

The demand for high-performance buildings has increased significantly due to economic development, urbanization, and rising living standards. Building occupants prefer a comfortable environment that directly improves their productivity, cognitive performance, and health (Zhang, 2019). Despite being passive, windows heavily influence interior lighting and temperature conditions. As a barrier between the inside and outside climates, windows are responsible for guiding solar radiation efficiently.

The domain of this problem is solar radiation, a form of electromagnetic radiation with wavelengths between 300 nm and 3000 nm. This range is split into three categories: infrared (IR) 300 nm - 380 nm, visible 380 nm - 780 nm, and ultraviolet (UV) 780 nm - 3000 nm (Ahmad, 2010). Infrared radiation represents 50% of solar radiation energy and is invisible to humans (Niu, 2021). To optimize energy consumption, window technologies fix the infrared transmittance based on the interior climatization requirements.

Emerging glass technologies (known as “smart windows”) are poised to transform energy-efficient architecture. Smart window development focuses on visual comfort and energy efficiency (Mustafa, 2023). By dynamically directing sunlight, smart windows can improve visual comfort while reducing the energy consumption of lighting and HVAC systems without the constraint of fixed configurations. Some smart windows utilize active power to switch between certain states, while others rely on chemical reactions that change window characteristics (Ke, 2019). This paper discusses the advantages and drawbacks of certain variants of smart windows and conducts an experiment to calculate performance metrics for several real-world window setups.

1.1 Thermal performance metrics

The solar heat gain coefficient (SHGC) measures the ratio of solar radiation transmitted directly through a configuration (Abolghasemi Moghaddam, 2023). In Figure 1, this represents the ratio of incoming light to transmitted light.

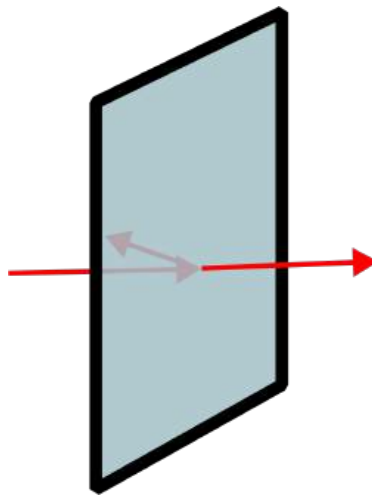


Figure 1 Solar Radiation Reflected and Transmitted through a Window

Since 50% of solar radiation is invisible near-infrared radiation, the SHGC can be altered without significantly changing the visual transmittance (Niu, 2021). However, traditional window technology is inflexible as the SHGC is a fixed parameter of the window configuration, meaning that environments with varying climates have the potential to benefit from windows with a dynamic SHGC (Arasteh, 2003).

The thermal transmittance U-value measures how much heat passes through a window per unit area and per degree of temperature difference, with lower values indicating better

insulation (Ficco, 2015). In both heating and cooling-oriented climates, a low U-value is desired as it reduces the effect of outside temperature on the interior (Rhine, 2008). Low U-values are typically achieved through a series of layers called glazings, sometimes with insulating air gaps to prevent quick thermal conduction (Perumal, 2024).

1.2 Electrochromic windows

Electrochromic windows, invented in 1961, were the first successful active smart window variant (Deb, 1973), and are used in digital low-voltage devices (Gu, 2022). Electrochromic devices can change optical properties to control environmental conditions based on electric switches (Fathi & Kavosi, 2021; Aguilar-Santana, 2020). Electrochromic windows utilize electrochromic layers like tungsten oxide (WO_2) that change transparency in the presence of an electric field. Electrochromic windows are a five-layered structure comprised of an electrochromic layer (like tungsten oxide₂), an electrolytic layer, and an ion storage layer, all of which are sandwiched between two transparent conductors, shown in Figure 2.

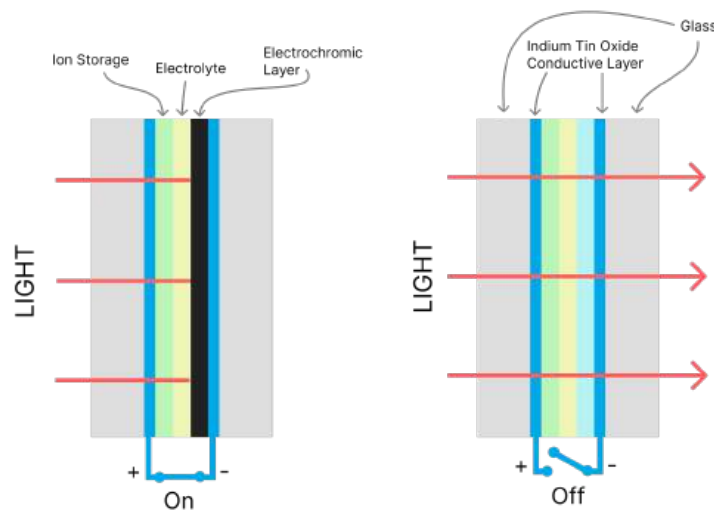


Figure 2: Electrochromic window diagram

When a powered circuit is closed between the conductors, electrons flow into the electrochromic layer, forcing positively charged ions to transfer through the electrolyte and react with the electrochromic layer to create opaque substances. Creating this charge difference typically peaks at 0.4 W/m^2 , but the energy required to maintain the state is zero. To revert to light transmission, the layers separate when the circuit is opened, causing it to return to its transparent initial state (Khaled, 2021). Electrochromic windows allow easy control of light transmittance at the expense of a small energy requirement.

1.3 Thermochromic windows

Thermochromic windows use materials that change color when exposed to heat. Thermochromic windows darken when the temperature is high, which follows when cooling

systems are active, and the SHGC should be low. Vanadium oxide (VO_2), Tungsten-Vanadium-Oxide (W-VO_2), and polymer-based thermochromic materials have been most successful in window manufacturing because their color-changing temperature is ideal for windows (Kamalisarvestani, 2013). Compared to electrochromic, thermochromic windows require no active power to operate, but don't offer dynamic control. However, this means the installation cost is much lower. Recent advancements have optimized thermochromic windows using neural network-based simulations (Lu, 2025).

1.4 Suspended particle device

Suspended particle device (SPD) windows switch transparency using rod-shaped microparticles. In the presence of an electric field, suspended particles align to allow light transmission. In the absence of an electric field, suspended particles face irregular directions, blocking light as shown in Figure 3. SPD windows can switch between blocking 40% of light at the minimum and 99.9% at most. Compared to other smart windows, SPD blocks UV and infrared radiation to the same degree as others wavelengths and have the advantage of variable dimming control at the disadvantage of cost (Nundy, 2019).

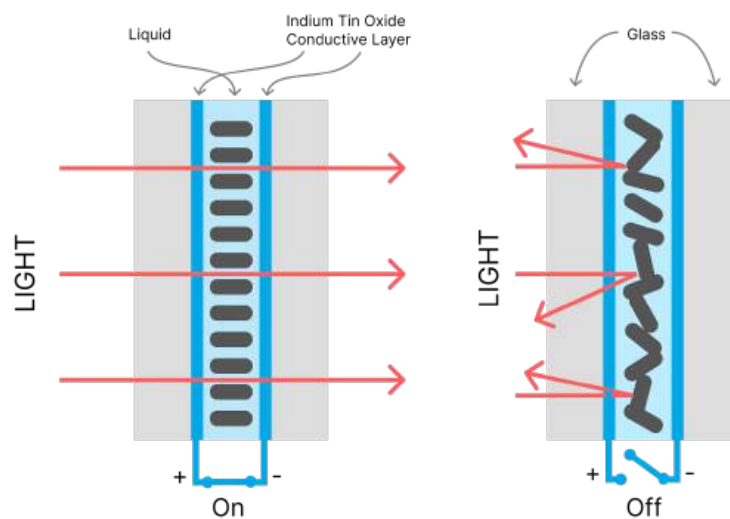


Figure 3: SPD window diagram

1.5 Polymer-dispersed liquid crystal

Polymer-dispersed liquid crystal (PDLC) windows use microdroplets of liquid crystal within a polymer matrix. This layer is situated between two electrodes that, when given an electric current, align the liquid crystals to allow light transmission. When the electrodes are not powered, liquid crystals scatter light, creating a foggy appearance perfect for dynamic privacy screens (Chang, 2022), as shown in Figure 4. The advantage of PDLC is that in its on-state, nearly 100% of visible light is permitted, but this comes at the cost of incomplete blockage in the

off-state (Hemaida, 2020). Since PDLC windows do not reflect or absorb much light, the change in the SHGC is negligible when comparing the translucent and transparent states.

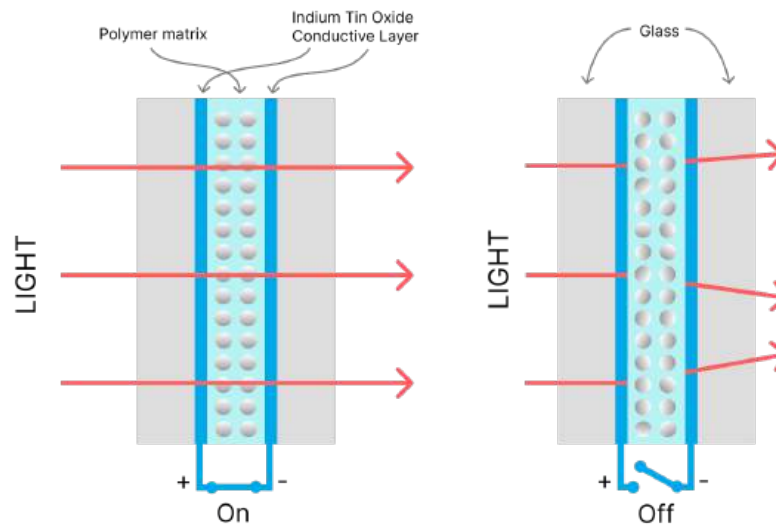


Figure 4: PDLC window diagram

1.6 Micro-blinds

As the newest of the smart window technologies discussed here, micro-blind windows use micrometer-scale curling electrodes to block or allow light through dynamically. On the other side of a thin insulator, a transparent conducting oxide layer conducts applied voltages, which generate an electric field that uncurls the micro-blinds, effectively blocking light (Marchwiński, 2014), as shown in Figure 5. The advantage of micro-blind technology is that when activated, the blinds reflect light rather than absorb it, reducing the SHGC because light is rarely absorbed and then retransmitted to the interior.

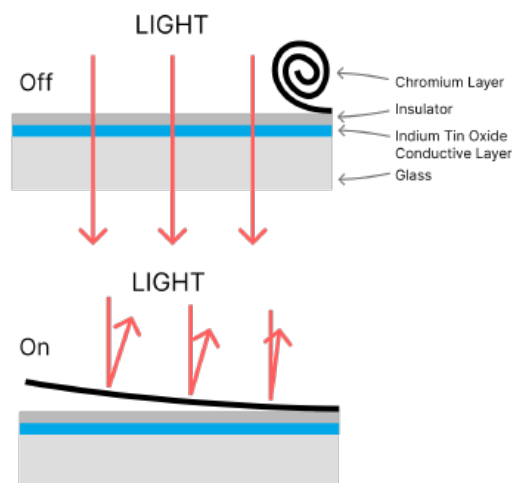


Figure 5: Micro-blinds diagram

1.7 Summary of Smart Windows

Window thermal performance is measured with the SHGC and the U-value, which are typically static as a configuration of the window setup. Newly developed smart windows are advantageous for their controllable optical transmission to meet occupants' thermal or visual comfort demands. Various smart windows are developed for different desired thermal characteristics. With the ability to change thermal characteristics dynamically, smart window setups have been integrated with Internet of Things devices to allow automatic and/or over-the-Internet control (Gunawan, 2017). With the aid of automatic control, smart windows are excellent candidates for changing energy-efficient architecture to reduce the energy consumption of interior climate control.

1.8 Previous Work

Citation	Windows Analyzed	Measurement method	Key Metrics
Hemaida, 2020	PDLC from HOHO film	Spectrophotometer. Compared the reference beam to the beam through the window.	SHGC changed by five percentage points between translucent and transparent states
Nundy, 2019	SPD from Smart Glass International	Illuminance sensors with 350 nm-820 nm spectral sensitivity	VLT was 0.38 and 0.02 for transparent and opaque respectively. Infrared light was affected much less than visible light.
Ghosh, 2016	SPD from Smart Glass International	Spectrometer in an enclosed box	VLT was 0.55 to 0.05 for transparent and opaque. SHGC was 0.38 for transparent and 0.05 for opaque. These statistics were for direct transmission, however the study assessed other angles.
Liang, 2018	Thermochromic of various coatings	Illuminance sensors in an enclosed box	Thermochromic window with largest variation in SHGC has a differential of 0.134
Omodaka, 2022	Electrochromic with custom design	Ratio of heat gain measured by heat exchangers	SHGC of 0.083 when tinted and 0.268 when transparent. This study used a custom system, so the low numbers are likely due to layering.
Piccolo, 2010	Electrochromic layer on Pilkington K-Glass	Photosensors and thermometer data in an air-flow box	SHGC of 0.53 to 0.12 from transparent to tinted. VLT of 0.681 to 0.06 from transparent to tinted

Table 1: Previous work in SHGC and VLT measurements of smart windows

According to previous work in Table 1, measurements for VLT and SHGC can vary significantly between studies, even when evaluating the same product (see Ghosh and Nundy). These inconsistencies may stem from differences in measurement methodologies, environmental testing conditions, sample preparation, or even subtle variations in the manufacturing process over time. This variability makes it difficult to draw direct comparisons or establish reliable benchmarks for performance across different smart window technologies (Li, 2025). This

highlights the urgent need for a comprehensive, standardized study that evaluates various smart glass systems—including PDLC, SPD, electrochromic, thermochromic, and the new micro-blind—using consistent testing protocols. This approach would not only improve the reliability of published data but also support engineers and scientists in making informed decisions regarding energy-efficient building fenestration design.

2. Methods

Optical experiments were performed to approximate values of the SHGC of certain kinds of smart window configurations. The smart windows tested were the white PDLC sample and the suspended particle device sample from the Gauzy Ltd smart window sample kit; the electrochromic from SageGlass sample kits; the micro-blind technologies from National Research Council Canada; and thermochromic glass samples from Smart Glass World. Despite most smart window technologies being manufactured as films, the products collected were sample windows with pre-applied films. Other window technologies like photochromic and gasochromic were considered; but were unavailable for research studies.

The light transmission and detection system is composed of three components. First is a mock sun source, the Philips LED Bulb A19 E26 Daylight, which consumes 8 watts of energy. To detect light from the bulb, an EKO Instruments MS-720 Spectroradiometer (wavelength range of 350 nm to 1080 nm) was used to measure the solar radiation passing through each window configuration. To measure electrical energy consumption, the window setup was plugged into a wattage meter.

Five control panes from Vitro Architectural Glass were obtained to validate the accuracy of the spectroradiometer. These were 4 by 6 inch panes with a thickness of 6 mm of their “Monolithic Glass Clear.” The manufacturer's specification states the SHGC is 0.82 and the VLT is 0.89.

2.1 Procedure

An empty room with no windows was prepared for the experiment. The edges of the door were covered with aluminum foil to prevent leakage of near-infrared light. The LED bulb was plugged into a hanging lantern extension cord and placed 1 meter above the space for a window sample. Underneath the window sample a spectroradiometer was used to measure light in all wavelengths. The spectra of each window variant in various configurations was recorded. Energy consumption was recorded as the power draw that the window drew from the wattage meter. The setup is represented in Figure 6, and a picture of the Gauzy SPD sample kit is in Figure 7.

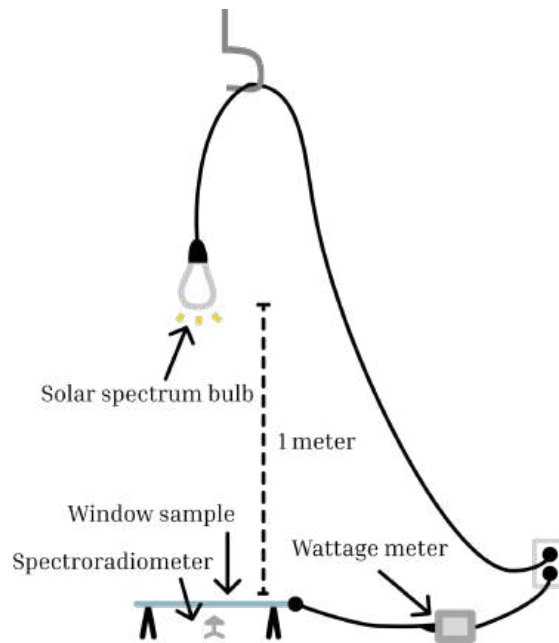


Figure 6: Experiment Setup

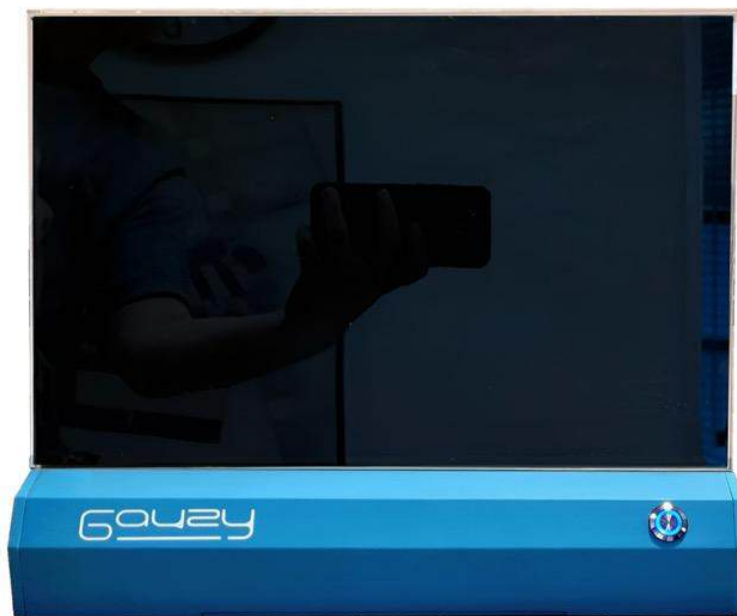


Figure 7. Picture of our Gauzy SPD sample kit

The spectroradiometer came calibrated at the factory; however, small changes in the angle of incidence can drastically alter the measurement. As such, the spectroradiometer was aligned to point directly at the lightbulb using a digital angle gauge.

For thermochromic windows, the room was heated or chilled to the desired temperature, and 5 minutes were given for the thermochromic window to match the environment temperature. Air temperature was measured with a thermometer and was within 0.5 °C of the data listed.

Each experiment was repeated 5 times with different samples to ensure consistency in manufacturing. The mean and standard error of each result are recorded in the results section. For the thermochromic measurement, the standard error is higher because room temperature is harder to control.

2.2 Data processing

To get the measured SHGC, the total wattage measured across the spectrum was divided by the wattage measured in the control sample.

Every SHGC measurement was transformed to account for the greater proportion of infrared light from the sun than from the lightbulb. The exact calculation is referenced in section 3.1.

3. Results

3.1 Control sample-based adjustments

The control sample measured the spectral irradiance of the lightbulb without a window. The irradiance of the dark room was found to be less than 0.01 W/m², so the background radiation is negligible. The total irradiance was 1.32 ± 0.01 W/m², and the total irradiance in the visible spectrum (380 to 700 nm) was 1.10 ± 0.01 W/m². The VLT for each window was calculated by dividing its measured pass-through irradiance by the control sample irradiance of 1.10 W/m².

The ratio of infrared to visible light in the lightbulb did not match the ratio in the sun, which has a 43% visible to 57% infrared split after ignoring other wavelengths according to ASTM G-173-03 (ASTM International, 2003), so we applied a linear equation to account for it. The lightbulb was measured to have an infrared irradiance of 0.22 W/m², so we divided the infrared irradiance by 0.22 W/m² to get the ratio of infrared passthrough. This ratio was multiplied by 0.57 and added to the VLT multiplied by 0.43. This final figure is written as the SHGC in the following section and is intended to be an accurate SHGC estimation using the solar spectrum.

The control sample from Vitro Architectural Glass confirmed the accuracy of the measurements of the spectroradiometer to within 0.02 for both SHGC and VLT measurements.

3.2 Data

The adjusted SHGC and measured VLT values are written in Table 2.

Technology	Configuration	Measured SHGC (dimensionless)	VLT (dimensionless)	Active Energy consumption (W/m ²)

Transparent	-	1.0 (by definition)	1.0 (by definition)	0
Clear Pane	8 mm	0.82 ± 0.01	0.89 ± 0.02	0
Thermochromic	16 °C	0.39 ± 0.03	0.40 ± 0.03	0
Thermochromic	24 °C	0.23 ± 0.02	0.25 ± 0.06	0
Thermochromic	32 °C	0.10 ± 0.05	0.13 ± 0.01	0
Electrochromic	Transparent	0.44 ± 0.02	0.44 ± 0.03	0
Electrochromic	Opaque	0.16 ± 0.01	0.39 ± 0.01	0
PDLC	Transparent (on)	0.41 ± 0.04	0.61 ± 0.04	4.6 ± 0.3
PDLC	Translucent (off)	0.33 ± 0.03	0.52 ± 0.03	0
SPD	Transparent (on)	0.40 ± 0.01	0.61 ± 0.01	4.6 ± 0.2
SPD	Opaque (off)	0.06 ± 0.01	0.01 ± 0.01	0
Micro-blind	Transparent (off)	0.38 ± 0.03	0.44 ± 0.02	0
Micro-blind	Opaque (on)	0.04 ± 0.03	0.05 ± 0.01	5.1 ± 0.2

Table 2: Summary of window performance metrics

The SHGC depends greatly on the type of window under the smart films. Since a different manufacturer makes each smart window sample with differing goals, the actual measurements of the SHGC should not be the main takeaway of this study, but rather the comparisons. With these metrics, the optimal smart window can be discussed.

3.3 General results

The electrochromic window can change its transmittance between two states that require no energy to maintain. The switching time for this sample was around 30 seconds, and the window drew power while switching. The advantage of this window is its low power use and relatively wide range of SHGC. Additionally, electrochromic windows are cheaper than other variants of heat-blocking smart windows. The electrochromic windows mostly matched the manufacturer's results of SHGC from 0.48 to 0.09; however, we were not able to replicate a SHGC specifically that low.

The PDLC variant was found to have only minor differences in transmittance between each state. This is likely because it is designed for privacy rather than changing the visible transmittance for either heating or cooling. The VLT was found to be much lower than the manufacturer's specification of 0.8 to 0.65; however, the sample may be transposed onto different glass.

The SPD window performed best out of the commercially available smart window technologies. The window did not perform equally on SHGC and VLT, showing that it is slightly

ineffective at blocking infrared light, supporting the results in Nundy (2019). The SPD window VLT approximately met the manufacturer's specification of 0.50 to 0.01.

The micro-blind variant performed most strongly, bringing a ratio of SHGC of almost 10 to 1. Additionally, the micro-blind technology affected both SHGC and VLT equally, whereas the SPD window was less effective at blocking IR light. Another key difference between SPD and micro-blind is that micro-blind blocks light while a voltage is applied, meaning the power-consuming phase would only be applied while the window is tinted. Paired with a switch that can modulate the voltage, this setup can be a commercially viable replacement for blackout curtains, which are intended to block all light.

The thermochromic window was found to change both the SHGC and VLT effectively with the different temperature environments, presenting a greater range of variability than (Liang, 2018); however, there may be a difference in the temperature range and coating. Thermochromic will be a viable option for buildings where wiring installation can be costly. We were unable to obtain the manufacturer's expected SHGC and VLT.

4. Discussion

With these results, region-specific smart window suggestions will be discussed, and the efficiency of smart window configurations can be assessed. Both micro-blind and SPD technologies performed similarly; however, they have different activation polarizations. Since the window surface area of a building can be hundreds of square meters, choosing the right window variant is critical to reducing window power consumption. Micro-blind technologies are better in this regard because the passive state (transparent) would be desired during most of a 24-hour day.

4.1 Region-specific results

As the desired SHGC varies from region to region, these results cannot create a conclusive, single recommendation. However, the United States Department of Energy has suggested static SHGCs for different geographical regions, which are reproduced in Figure 8 and Figure 9.

ENERGY STAR® Certification Criteria for Residential Windows

WINDOWS			
Climate Zone	U-Factor ¹	SHGC ²	
Northern	≤ 0.22	≥ 0.17	Prescriptive
	= 0.23	≥ 0.35	Equivalent Energy Performance
	= 0.24		
	= 0.25	≥ 0.40	
	= 0.26		
North-Central	≤ 0.25	≤ 0.40	
South-Central	≤ 0.28	≤ 0.23	
Southern	≤ 0.32	≤ 0.23	

Air Leakage ≤ 0.3 cfm/ft²

¹ Btu/h-ft²·°F

² Solar Heat Gain Coefficient

Figure 8: Energy Star® Climate Zone Window Recommendations

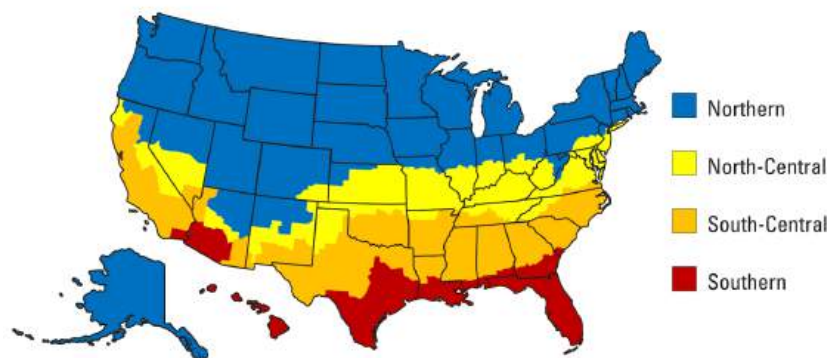


Figure 9: U.S. Department of Energy Climate Maps

Northern: These zones have average yearly temperatures below 6 °C. This region desires a high SHGC to heat the building with solar energy instead of traditional techniques. Traditional windows or any smart window variant can be suitable. If toggleable privacy is desired while keeping similar lighting, the PDLC smart window is a good option.

North-Central: These zones have average yearly temperatures between 6 and 18 °C. This region is temperate with occasional heat waves. In situations where wiring will be complicated, the ideal window would be thermochromic since it would require no active power. In new

buildings, installing electrochromic windows will allow more dynamic control at the cost of additional wiring. Both can reach the recommended SHGC of below 0.4 when cooling demands are required.

South-Central and Southern: These zones have average yearly temperatures above 18 °C and require a high demand for cooling. The ideal window for this region would be SPD or micro-blinds since they both block a majority of the bright sunlight that is undesirable during summer, and both of their opaque modes meet the recommended guidelines of an SHGC below 0.23.

These U.S.-based recommendations can be broadly applied to international regions that have similar climate characteristics. For example, Southern Europe (e.g., Spain, Italy) and parts of the Middle East share climate traits with the South-Central U.S., making SPD or micro-blind technologies ideal. Globally, the average yearly temperature recommendation is a key consideration in deciding on smart window choice (De Masi, 2022), so the yearly average temperature guidelines we outline should be followed.

4.2 Limitations

While this study does analyze a large spectrum of electromagnetic radiation through the window, it does not measure the energy absorbed since this would require a full measurement of the light reflected by the window, which, in practice, is hard to measure without specialized equipment and a light source more similar to the sun. To address this limitation in future work, the calorimetry hotbox method, as outlined in ISO 19467-2, should be employed.

Furthermore, the study does not consider the full spectrum of light emitted by the sun; it only uses a lightbulb that emits mostly visible and near-infrared light. A full analysis would also include the UV spectrum.

This study also does not consider the difference in SHGC based on the angle at which the sun strikes the window. However, traditional techniques for measuring SHGC do not account for angled setups (Kontoleon, 2015).

The cost effectiveness of these windows could not be compared as new manufacturing techniques may dramatically reduce the price, and some technologies like micro-blinds are not yet sold for market purchase. According to manufacturers like Smart Glass World, thermochromic and PDLC are approximately the same price, electrochromic is more expensive than both, and SPD is more expensive than electrochromic (Smart Glass World, 2024).

4.3 Future Windows

In the future, smart windows that can change their SHGC independently from their visible light transmittance will be ideal for optimizing visual and thermal comfort (Gundogdu, 2024). Currently, there may be a mismatch between the ideal infrared transmittance and the ideal visible transmittance in the case where thermal comfort and visual comfort have different demands. In order to achieve this, a possible dual layered system where one layer controls the visible light transmittance and another layer controls infrared light transmittance could be

feasible. This study found that SPD windows block visible light more effectively than infrared light. Combined with a switchable version of a low-e glazing, an advanced window allowing independent control of the two spectra could be possible.

4.4 Practical Barriers

While smart windows have great potential for energy savings, several barriers limit their widespread adoption. For instance, electrochromic and SPD windows typically require electrical wiring, which can be costly to install or retrofit—especially in existing buildings. Thermochromic windows may lack user control, as their functionality depends on the ambient temperature rather than occupant preference. PDLC windows are better suited for privacy than energy savings, and their visibility can become uneven at larger scales. Micro-blind technology is still in the research phase and not yet commercially available (Marchwiński, 2014). Although SPD windows are available on the market, they remain difficult to obtain due to high licensing costs and a limited number of manufacturers (Ghosh, 2024). These limitations must be addressed before smart window technologies can achieve widespread and practical implementation in buildings.

5. Conclusion

Smart windows are poised to change the world of energy-efficient architecture and revolutionize interior design. With privacy screens like PDLC already available on the market, emerging technologies like SPD and micro-blinds will enhance building energy efficiency, which represents a large portion of greenhouse gas emissions.

This study assessed the SHGC and VLT of various smart window setups in various conditions. In reality, these window technologies will be applied as films to other window setups that already have a high SHGC. These films, however, will allow a way to change the light transmittance. For new “smart” windows, the light transmittance can be changed with active electric power, and for thermochromic windows, changed with outside temperature

Smart windows will be critical to battling climate change, as interior climatization technologies are the largest portion of building-sector emissions. Regional climates where the temperatures vary will benefit the most from smart windows, as they will be able to stay warm in the winter and cool in the summer without as much active interior climate control.

This study assessed the performance of one passive technology and four active technologies. The final recommendations are that regions with a yearly average temperature above 18 °C should install SPD or micro-blind windows because they block the most solar radiation at 94% and 96%, respectively. For regions with yearly average temperatures between 6 °C and 18 °C, electrochromics or thermochromics should be employed because they are cost-effective. Regions with yearly average temperatures below 6 °C should install PDLC or traditional windows. Until micro-blind technologies become available on consumer markets, SPD will be a great option for buildings in hot climates to save energy costs.

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CRISPR/Cas9: The Potential Innovative Approach to Treat Crohn's Disease By Ilinca Sasu

Abstract

Crohn's Disease is a chronic disease that causes severe inflammation in any part of the patient's gastrointestinal tract. This condition affects the health and well-being of up to five million people worldwide. There is no cure for Crohn's disease. There are currently only treatments to help manage symptoms or improve the quality of life for patients, such as reconstructive bowel surgery, antibiotics, and biologics therapy. Biologics intend to neutralize the proteins that cause inflammation and are currently the most popular treatment approach. However, they don't work well in some cases and can cause further complications. These complications are linked with a known mutation in the ATG16L1 gene. CRISPR/Cas9 is a promising gene-editing technology that has been widely developed for the treatment of various diseases. This project aims to incorporate CRISPR/Cas 9 technology to correct the ATG16L1 gene rs2241880 T300A mutation in Crohn's disease patients by selecting a potential target site for the CRISPR complex. The software CHOPCHOP was the best choice for the project because of its easily accessible format and in-depth results and analysis. Out of 157 target sequences, we noted that Rank 39 was the best CRISPR site because of its ideal GC content and overall efficiency ranking of 74%. If this treatment worked, it would help the 10-30% of people who don't respond properly to Infliximab. The data obtained in this project provide useful information for the development of CRISPR/Cas9 therapy for the treatment of Crohn's disease to improve the effectiveness of existing biologics therapy.

Introduction

Crohn's Disease is a type of Inflammatory Bowel Disease (IBD) in which patients experience chronic inflammation in any part of their digestive tract, ranging from the rectum to the mouth. Symptoms include bloody stools, fatigue, diarrhea, and abdominal pain (3). In more severe cases, reconstructive surgery is required to protect the gut and prevent debilitating digestive diseases such as colon cancer. The Crohn's and Colitis Foundation notes that approximately 70,000 new cases of Crohn's Disease are diagnosed annually (28). Overall, around 2.4 to 2.8 million people in the United States and 6-8 million people worldwide suffer from the condition (28), and this number is only rising.

Different treatments for Crohn's Disease include anti-inflammatory drugs such as prednisone, antibiotics, reconstructive surgery, and biologics. Biologics are a class of therapies that target proteins generated by the immune system during inflammation, called Tumor Necrosis Factor-Alpha (TNF- α). Biologics can target these proinflammatory proteins that cause inflammation by neutralizing their signals. Some commonly used biologics include Infliximab, Adalimumab, and Golimumab, all of which are TNF Inhibitors (**Figure 1**). TNF Inhibitors neutralize Th1 cells that activate macrophages by releasing cytokines (12). In many cases, these treatments work and help the patient reach remission; however, when they don't, it means one of two possibilities: the biologics are not effective for the patient and the disease progresses, or the

biologics cause side effects that could provoke the gut and cause further intestinal bleeding. Treatments for Crohn's Disease are highly expensive (25), costing \$8.5 billion in 2018 and increasing significantly after the fact (11). Biologics make up around 71% of all costs associated with Crohn's Disease, and Infliximab costs as much as \$12,000 per treatment session (1). A study conducted by the Canadian Journal of Gastroenterology and Hepatology found that at 54 weeks, around 63.6% of patients on Infliximab remained responsive (27). Despite this high success rate, 10-30% of people don't achieve remission with Infliximab (22). The number of people who don't reach remission is even higher with other TNF Inhibitors, meaning that a relatively large percentage of people who don't obtain remission with Infliximab may also react poorly to other biologics. Their last resort is surgery. However, reconstructive surgeries are invasive and risky, potentially worsening the patient's quality of life due to complications. Biologics are significantly less invasive and, therefore, a more sustainable method of rehabilitation for the patient. However, when a biologic doesn't work properly, causing further complications and increased presentation of symptoms, it begs the question: is there another way to treat these patients?

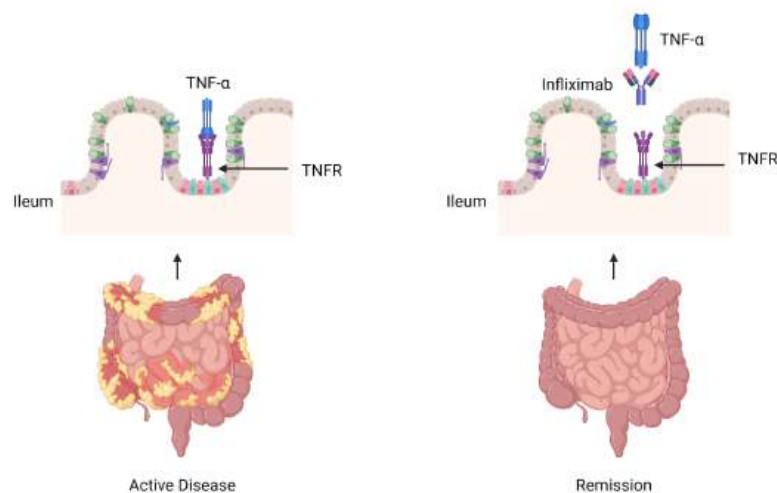


Figure 1: Mechanism of action for Infliximab. Infliximab is a TNF-alpha inhibitor that neutralizes the activity of the TNF that promotes inflammation as part of the immune response and blocks TNF- α from binding to its receptor, which intercepts communication between immune cells. TNF- α inhibitors reduce the expression of immune molecules that adhere to the inflammation site and reduce the expression of immune molecules involved in invasion (10).

A study by Feuerstein et. al. (8) suggests that Crohn's Disease is caused by a plethora of environmental and genetic factors. Aside from smoking and poor diet, many environmental factors include the following: stress, anxiety, depression, and lack of exercise. However, these factors only account for individual lifestyles. People who live in hygienic environments have reduced exposure to bacteria and viruses, which can lead to an imbalance between the exposure and immune response (4). Air pollutants, including nitrogen dioxide, pose a risk to developing

Crohn's Disease. While these factors can worsen the risk of developing Crohn's Disease, being exposed to these threats doesn't mean it will happen. It also poses the question: why do some people develop Crohn's Disease while others don't, despite living with the same conditions? Genetics plays a much larger role in Crohn's Disease than environmental factors. Those with certain genetic mutations are more prone to suffering from this chronic illness. Some of the most prevalent genetic mutations in Crohn's Disease are the *NOD2* mutation and the *ATG16L1* mutation. The *NOD2* gene is prevalent in the intestinal wall (7) and serves to protect the lining from antigens. Epithelial cells within the intestinal wall express the *NOD2* gene and demonstrate the highest level of expression in dendritic cells (21). If this gene is mutated, it may disrupt the immune system's natural detection system, which can attack harmless bacteria in the gut and promote inflammation. The *ATG16L1* gene is also active in the immune response, detecting antigens and harmful bacteria in the gut (23). This gene is located and most active in lymphocytes, which are the body's natural defense system that attack antigens. For this study, we decided to focus on the *ATG16L1* gene (**Figure 2**). This is where Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR) technology comes in. CRISPR/Cas9 are gene-editing techniques utilized by bacteria to attack invading viruses (16). Doctors have only recently begun to use it in treatments such as Sickle Cell Disease (5) and Leukemia (26). This could be important to implement in Crohn's Disease because if this treatment is proven successful, it may be able to prevent mutation-related rejection of biologics treatment and contribute to the cure of Crohn's disease.

The objective of this project is to experiment with mutated genes using CRISPR editing (19) to be able to alter a specific mutated gene (*ATG16L1*), resulting in the patient who uses the therapy to become responsive to biologics.

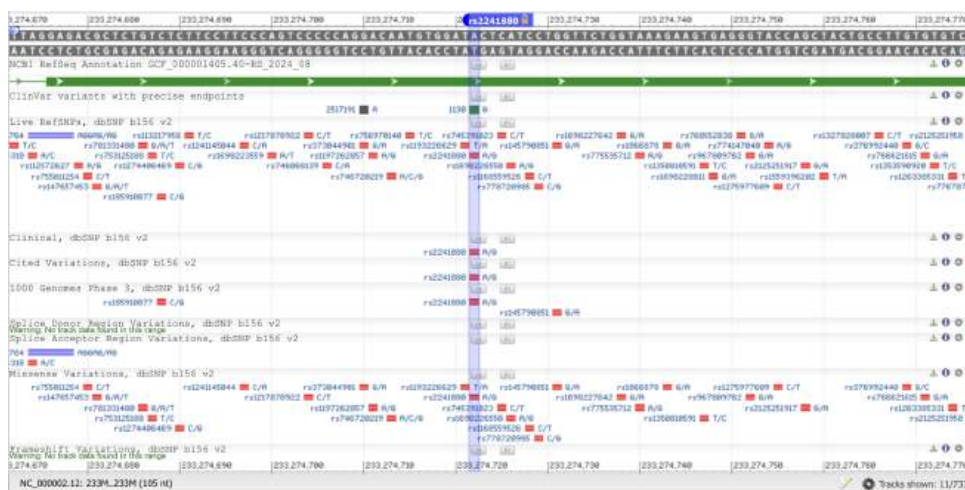


Figure 2: A closer look at the *ATG16L1* rs2241880 T300A mutation. UCSC Human Genome Browser detected the *ATG16L1* gene sequence and the *ATG16L1* rs2241880 T300A mutation, and where the mutation impacts the sequence.

Beginning this project, I synthesized any information on CRISPR-Cas9 technology and its implementation into Crohn's Disease. A study conducted by the World Journal of Gastroenterology in 2013 discovered that CRISPR/Cas 9 technology has been attempted on a mutation of the IL-10 gene, but ultimately found that the experiment had little to no effect on patients (18). Even if the IL-10 gene isn't targetable, perhaps other genes involved in Crohn's Disease are.

Hypothesis

I hypothesize that CRISPR/Cas9 gene editing could help improve the effectiveness of biologic Infliximab for Crohn's Disease by reversing the *ATG16L1* rs2241880 T300A mutation associated with non-responsiveness to Infliximab.

Methodology

The first step in completing this project was to identify the population that this approach would apply to. Essentially, the population we planned to test on should be those using treatments for 1 year that did not lead to remission. We classified remission into five categories: clinical remission, biochemical remission, histological remission, endoscopic remission, and surgical remission. Clinical remission is defined as a patient who doesn't present with any symptoms of a Crohn's Disease flare-up. Their condition is essentially dormant. Biochemical remission is identified through lab tests, including blood tests and stool tests that examine calprotectin levels as well as white and red blood cell count, vitamin B12, D, and iron levels. Ideally, these substances should be within the normal range for a patient to be classified as in biochemical remission. Endoscopic remission searches for inflammation in the lower gastrointestinal region. A patient without any ulcers or intestinal bleeding would be considered in endoscopic remission. Histological remission detects inflammation at a microscopic level, determining that a patient without any inflammation in the tissue taken from a biopsy is in histological remission. The final type of remission is surgical remission, when a patient experiences no inflammation after removing the diseased portion of the gut through surgical procedures. Clinical and biochemical remission are considered the first and second phases of a patient's condition. Those who don't demonstrate remission in these phases would have to move on to endoscopic and histological testing, phases three and four. In some cases, however, the disease advances so quickly that surgery is required to bring the patient to surgical remission.

Of the over 160 genes associated with Crohn's Disease, we identified the gene most directly correlated with the condition. *ATG16L1* has demonstrated high involvement in immune processes against antigens, making it an optimal target for gene editing. More specifically, we targeted the mutation rs2241880 variant T300A (24), which changes the 300th out of 43,000 amino acids in the sequence, where base pair Adenine is found in place of Guanine, which has been demonstrated to promote inflammation. We needed to identify the specific mutation within the gene's genome and run the sequence through a CRISPR/Cas 9 program to edit the mutated nucleotide and replace it with a healthy one. The three types of genetic testing are cytogenetic,

biochemical, and molecular. Cytogenetic testing examines chromosomes for abnormalities. Biochemical testing detects irregularities in the proteins being produced by genes. However, molecular genetic testing inspects DNA mutations, which was suitable for this project because the gene that we tested had a mutation in its DNA base pair. We ran the mutated gene sequence through CHOPCHOP, which created a single guide RNA molecule (sgRNA). An sgRNA is a fusion of a custom-designed CRISPR RNA (crRNA) sequence and a scaffold transactivating crRNA (tracrRNA) sequence. We used the sgRNA format because it is simple and easy to customize. The sgRNA identified the correct location for the Cas 9 nuclease to perform editing.

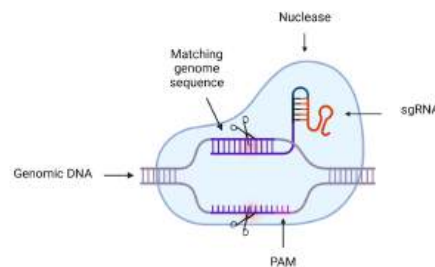


Figure 3: CRISPR/Cas 9 at work

CRISPR/Cas 9, with the help of a single-guide RNA, identifies the target location and cuts the mutated part of the sequence. Then, CRISPR molecules replace it with the correct nucleotide.

Our target group is the 10-30% of people who don't respond positively to Infliximab (22), meaning that they didn't achieve clinical or biological remission within the expected timeframe of thirty weeks within the first administration of the medication. Essentially, these patients are stuck in the first and second stages, unable to obtain blood tests that determine that their calprotectin levels are normal or achieve a dormant condition. If the treatment has proved to be effective for the patients in the first and second stages, we would test it on patients with more severe inflammation. The second phase of the experiment is testing on those who have more severe cases and are experiencing symptoms that align with the disease's presentation in stages three and four.

Reconstructive bowel surgery is highly expensive and invasive, and its success in bringing a patient to remission is not guaranteed. Reconstructive bowel surgeries can cost anywhere from \$6,000 to \$50,000 (1) without insurance. A study performed by Johns Hopkins University in 2020 demonstrates newer technologies that allow gene editing therapy to work within minutes after being administered, allowing the modified gene to act instantly. In theory, we would be able to determine if the gene editing therapy worked for the patient within one to two doses. The gene editing therapy intends to help patients reach remission with this, and the added help of biologics. Thus, we intend to develop a new and more cost-effective treatment that has a higher

likelihood of helping a patient reach remission. To test the outcome of this theory, we would have to track responses to biologics after gene editing has been performed.

There are a multitude of factors that can cause Crohn's Disease, and we won't be able to cure it with just one treatment. Environmental factors are largely uncontrollable and inevitable. However, we strive to increase the chances of reaching remission and taming this condition at its source.

Procedure

Below is an outline describing all steps of the full procedure. Here, we have only completed part 1, but the remainder of the procedure is meant to serve as a guideline for how the project should be approached if it were to be completed in a lab.

1. **CRISPR Design:** Design sgRNA targeting the *ATG16L1* gene.
2. **Delivery:** Introduce CRISPR-Cas9 into the cells.
3. **Target Editing:** Cas9 introduces a DSB at *ATG16L1*.
4. **DNA Repair:** NHEJ or HDR modifies the target gene.
5. **Sequencing:** Extract DNA, amplify the region, and sequence to confirm edits.

PART 1: CRISPR Design

This is the only part that was completed. The remaining four parts are for future research involving the work in this paper.

- Select the CRISPR-Cas9 targeting sequence of the target gene (*ATG16L1*) in the genome
- Choose two or more sgRNAs provided by the Cas9 program (CHOPCHOP) for creating the primers (starting points to the left and right of the target sequence that are required to edit the DNA sample)

PART 2: Delivery

- sgRNA design (must-have for experiment) with primers that serve as starting points for the DNA sequencing
- Deliver the sgRNA to the cell either through plasmid delivery (inserting the sgRNA sequence into the plasmid and introducing it into the cell) or Ribonucleoprotein delivery (preassembled sgRNA directly injected into the cell)

PART 3: Target Editing

- The Cas9 protein, guided by the sgRNA, will bind to the target sequence (as mentioned in PART 1) and introduce a Double-Strand Break, which triggers a DNA repair response that incorporates the edited sequence into the gene

PART 4: DNA Repair

- DNA repair through Non-Homologous End Joining (NHEJ), which aims to fix the double-strand breaks
- NHEJ is prone to causing insertions/deletions (indels) that cause frameshifts in the genetic sequence

PART 5: Sequencing

- After editing, use DNA sequencing to extract genomic DNA
- Use the primers from PART 2 to get to the edited site of the *ATG16L1* gene, and Polymerase Chain Reaction to detect and evaluate the CRISPR-induced changes
- Use Next-Generation Sequencing to analyze potential off-target effects and edits
- Compare the edited *ATG16L1* gene sequence to the original gene sequence

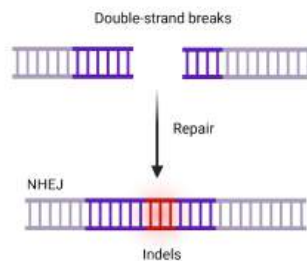


Figure 4: A visual representation of DNA repair through NHEJ

Non-Homologous End Joining helps repair the work that CRISPR/Cas 9 did by rejoining ends of a double-strand break directly.

Results

The *ATG16L1* gene was the most ideal selection for this treatment because it facilitates autophagy, a process in which cells recycle fatigued parts and aid in eliminating harmful bacteria and viruses in the gut. Additionally, the gene controls inflammation, modulates the immune response, and works to maintain homeostasis. Since *ATG16L1* has high expression in immune cells, it is most directly involved in the immune and inflammatory response, thus making it a valuable asset for a potential treatment for Crohn's Disease. However, certain genetic variants can cause this gene to promote inflammation. For example, rs2241880 T300A is a genetic variant that is a single nucleotide change in the DNA and has a high association and prevalence in patients with Crohn's Disease.

Out of numerous CRISPR/Cas9 design programs, we chose CHOPCHOP (14, 15, 16, 20) because it used the same Genome Reference Consortium Human Build (GRCh38) as the sequence. The GRCh38 format provides a significantly wider range of protein-coding genes than

its predecessor. CHOPCHOP also provided several sgRNA designs, categorized them based on Guanine Cytosine (GC) Content, and dispensed multiple primers for each sgRNA. It even provided the risk of off-target effects for all sgRNA designs. We only completed step one, the computational model, out of a five-step process that involves lab testing.

GC nucleotide pairings are often stronger than AT pairings because they are more thermally stable. This stability allows DNA to become resistant to denaturation, a process where a protein or nucleic acid loses its three-dimensional structure due to factors including heat, pH level changes, chemical changes, and external forces. This additional stability is because guanine forms three hydrogen bonds with Cytosine, whereas Adenosine only forms two hydrogen bonds with Thymine, which is why GC pairs are more resistant. GC content is highly important to take into account for genome editing and DNA sequencing. When a GC Content percentage is too high, complications such as interferences with the annealing primers may occur (13). Additionally, a GC content that surpasses 70% is more likely to form secondary structures, hindering accurate analyses of the sequence (9). Similarly, when the GC content is lower than 30%, it becomes less stable and less able to resist denaturation. The best possible percentage range for GC content is around 50-55% (2). However, a sequence can have a GC content as low as 35% or as high as 60% and still maintain its natural resistance properties.

Off-targets are unintended insertion (adding an extra base pair), deletion (removing a base pair), point (switching base pairs), or frameshift mutations (inserting or deleting multiple base pairs at a time) that are similar to the target site. Mutations can be dangerous because they don't produce the proper amino acids that they typically would, which can cause irregular functioning of the gene or the gene to not function at all. This can lead to potential development problems or mutated cell growth, which can result in cancer. These are important to consider given that some sgRNAs provide a greater or lesser risk for off-target effects, and based on this data, we can determine which sgRNA designs are the most effective for this method of treatment.

Next Generation Sequencing (NGS) is a technique commonly used to detect off-targets. As mentioned previously, primers are the starting points for DNA synthesis. GC content impacts the effectiveness of primers because it determines their binding stability to the DNA and influences optimal primer specificity and annealing, reconstruction, and temperatures. CHOPCHOP labels off-targets as MM1s, MM2s, or MM3s, which indicates how many pairs of mismatches occur with a given sgRNA design.

A table of the top 5 most effective target sequences out of 157 sequences from CHOPCHOP has been compiled, taking into account self-complementary factors, efficiency, GC content, and off-target effects (**Table 1**). These individual rankings were compiled with the overall efficiency of the sequence as the main indicator of its success.

Table 1: Target sequences ranked from one to five based on **GC Content**. Note that the rank identifications are not associated with the actual ranking of the sequences and primers.

	Target Sequence	Genomic Location	Strand	GC Content

Rank 5	AAGCTCATCCATCAATGCG GTGG	Chromosome 2; coordinates 233294254	+	50%
Rank 47	GCTAAGAGGTAAGATCCCT GTGG	Chromosome 2; coordinates 233282676	-	50%
Rank 8	GACAATGCGCGGATTGTCT CAGG	Chromosome 2; coordinates 233289905	+	55%
Rank 39	CATACTTACGAAGACACAC AAGG	Chromosome 2; coordinates 233274765	-	40%
Rank 1	GGTTCCCGGTTACTGGCCA CTGG	Chromosome 2; coordinates 233277610	+	65%

Table 1 demonstrates that Rank 5 is the most ideal selection for CRISPR/Cas 9 editing because its GC Content is within the most optimal range. However, Rank 47 could also be a potential option because its GC Content is the same as that of its competitor.

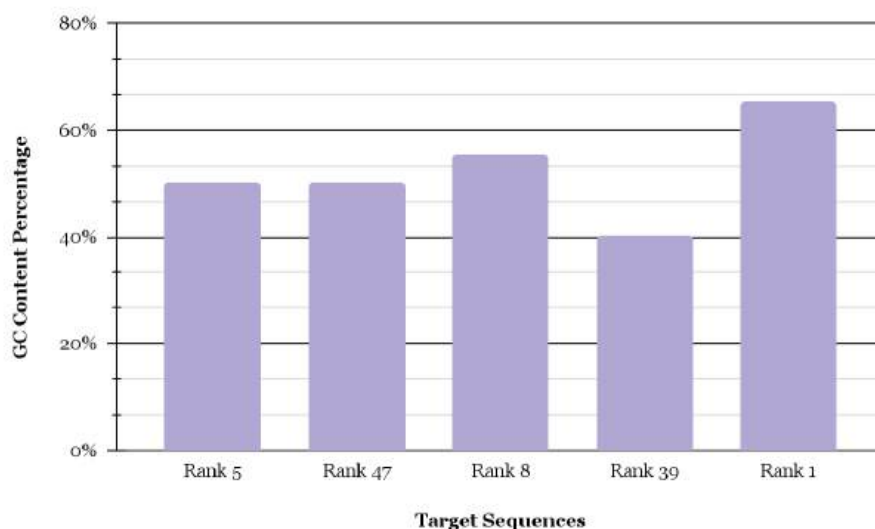


Figure 5: Graphical representation of GC Content

Table 2: Target sequences ranked from one to five based on their *Self-Complementary Strands*

	Target Sequence	Genomic Location	Strand	Self Complementary Strands
Rank 39	CATACTTACGAAGACACAC AAGG	Chromosome 2; coordinates 233274765	-	None

Rank 47	GCTAAGAGGTAAGATCCCT GTGG	Chromosome 2; coordinates 233282676	-	None
Rank 5	AAGCTCATCCATCAATGCG GTGG	Chromosome 2; coordinates 233294254	+	None
Rank 1	GGTTCCCGGTTACTGGCCA CTGG	Chromosome 2; coordinates 233277610	+	None
Rank 8	GACAATGCGCGGATTGTCT CAGG	Chromosome 2; coordinates 233289905	+	2

Notably, the sequences with no Self-Complementary Strands were more favorable than the ones with Self-Complementary Strands. Additionally, the negative strands are deemed more effective than the positive strands (the Efficiency Chart will demonstrate why this is the case). Although Self-Complementary Strands improve transduction, the results prove otherwise.

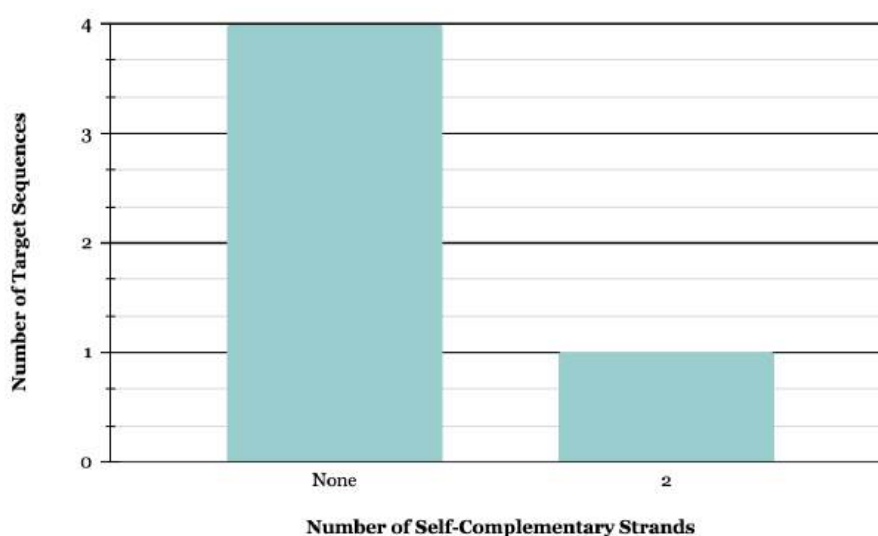


Figure 6: Graphical representation of Self-Complementary Strands

Table 3: Target sequences ranked from one to five based on the number of Mismatches (MM1s, MM2s, MM3s)

	Target Sequence	Genomic Location	Strand	Mismatches
Rank 1	GGTTCCCGGTTACTGGCCACT GG	Chromosome 2; coordinates 233277610	+	None
Rank 5	AAGCTCATCCATCAATGCGGT GG	Chromosome 2; coordinates 233294254	+	2 MM3s
Rank 8	GACAATGCGCGGATTGTCTCA GG	Chromosome 2; coordinates 233289905	+	2 MM3s

Rank 47	GCTAAGAGGTAAGATCCCTGT GG	Chromosome 2; coordinates 233282676	-	6 MM3s, 1 MM1
Rank 39	CATACTTACGAAGACACACAA GG	Chromosome 2; coordinates 233274765	-	7 MM3s

Rank 39 has the highest number of MM3s, while Rank 1 has the lowest amount. The average amount of mismatches in the five target sequences is 3, 2, and the median of the data is 2 MM3s.

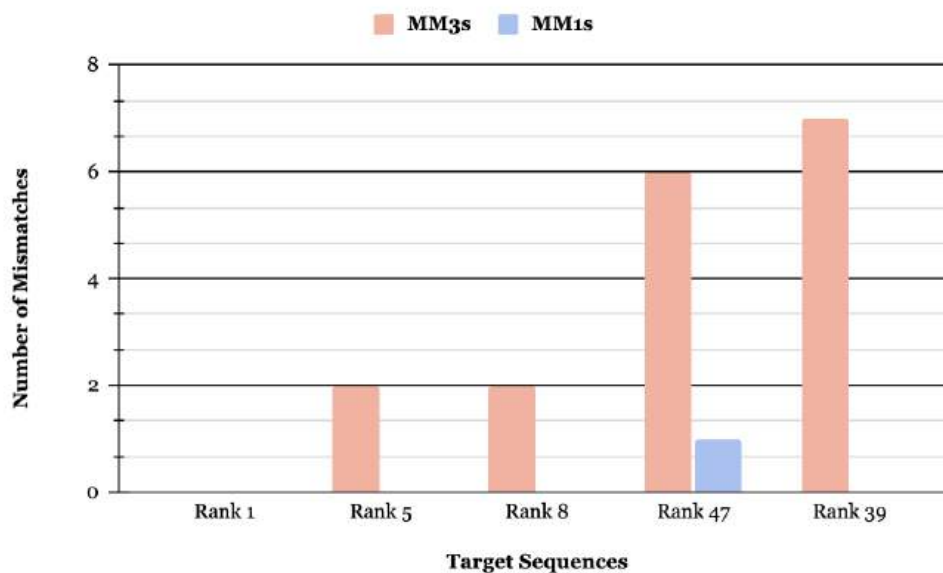


Figure 7: Graphical representation of Mismatches

Table 4: An overall ranking of the target sequences based on their Efficiency

	Target Sequence	Genomic Location	Strand	Efficiency
Rank 39	CATACTTACGAAGACACAC AAGG	Chromosome 2; coordinates 233274765	-	74.00%
Rank 47	GCTAAGAGGTAAGATCCCT GTGG	Chromosome 2; coordinates 233282676	-	68.09%
Rank 5	AAGCTCATCCATCAATGCG GTGG	Chromosome 2; coordinates 233294254	+	63.54%
Rank 1	GGTTCCTCGGTTACTGGCCA CTGG	Chromosome 2; coordinates 233277610	+	46.22%
Rank 8	GACAATGCGCGGATTGTCT CAGG	Chromosome 2; coordinates 233289905	+	41.85%

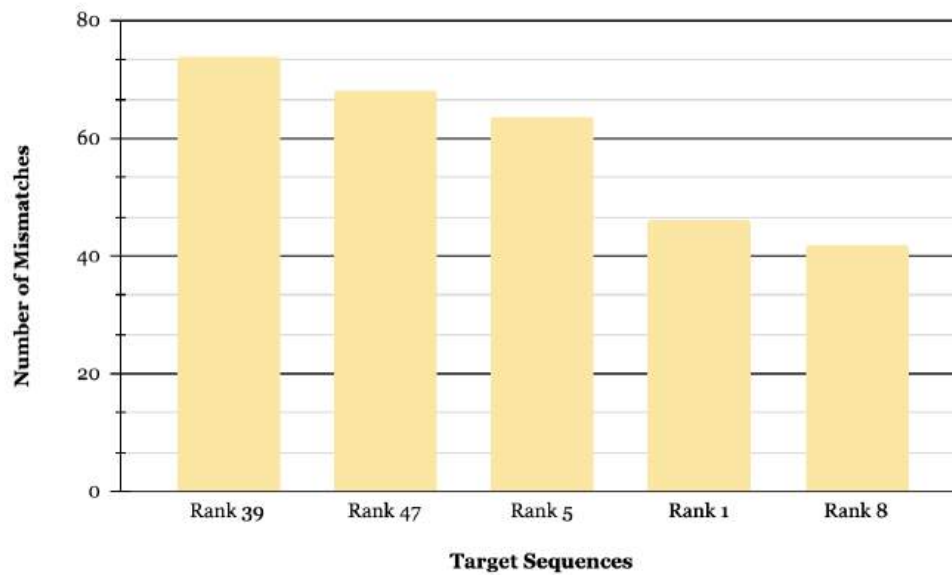


Figure 8: Graphical representation of Efficiency

Taking into account the numerous factors that impact a sequence's efficiency, it can be inferred that **Rank 39 is the best target sequence overall for CRISPR/Cas 9** to fix and correct the rs2241880 mutation in ATG16L1 because of its high efficiency, optimal GC Content, and relatively low number of mismatches compared to other target sequences (**Figure 7**). Its efficiency score was also one of the highest out of the 157 target sequences that CHOPCHOP compiled.

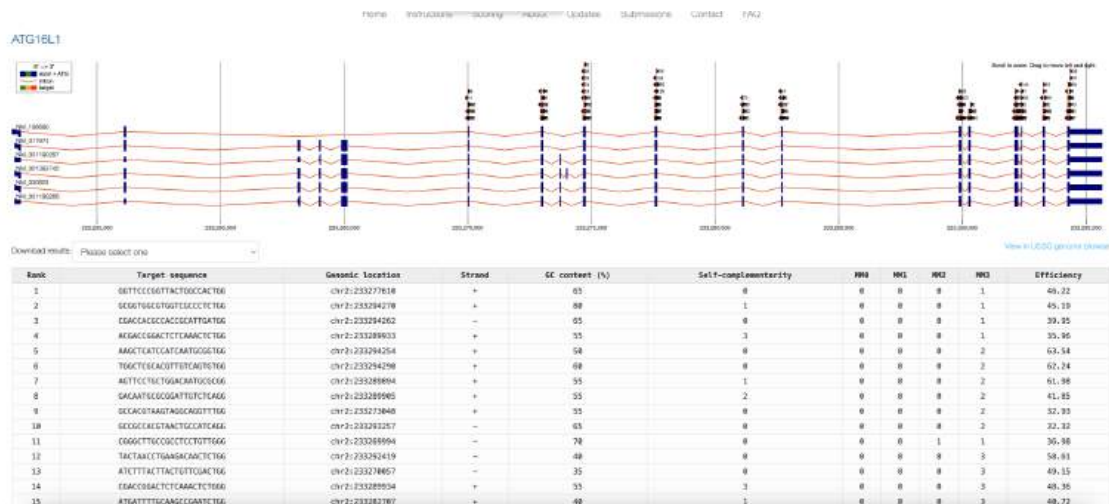


Figure 9: Digital representation of CHOPCHOP's rankings (target sequences)



Figure 10: Digital representation of CHOPCHOP's rankings (sgRNAs for Rank 39)

Outside of the top rankings that have been selected, there were a few notable outliers in the 157 target sequences. For instance, Rank 95 had a GC Content of 55% and three self-complementary strands; however, its efficiency score was a mere 4.51%, meaning it had only a 4.51% chance of finding its target. Even though it had 15 MM3s, many other sequences had up to 30 MM3s and still scored a significantly higher efficiency than Rank 95. This likely demonstrates that even the most ideal conditions for a target sequence don't necessarily determine its success.

The number of mismatches and off-targets did not indicate that the sequence would contain a lower efficiency rate. In fact, both Rank 39 and Rank 112 are examples of this. Rank 112 had an efficiency score of 75.06%, but it had 18 MM3s. Studies (6) have shown that mismatches can potentially enhance the editing efficiency because they introduce a certain amount of base pair differences within the sgRNA, which increases off-target sensitivity.

Some target sequences were rich in GC Content, but yielded poor results. For instance, most sequences with 70% GC Content scored efficiencies within 30-50%. While there were exceptions to this, this was a common pattern. The highest GC Content was 75% in Ranks 138 and 139, but both scored within the 50% efficiency range. Contrarily, sequences with GC Contents on the lower end of the spectrum consistently performed better, as demonstrated by Rank 39. Other sequences that prove this are Ranks 127 (62.27%), 156 (58.67%), and 90 (65.15%).

Self-Complementary Strands had little effect on efficiency, as the results that CHOPCHOP provided had varying statistics.

Conclusion

The effects of Crohn's Disease can be devastating to a patient, but a new method of treatment involving CRISPR/Cas 9 technology can help countless patients in a flare-up and save millions of dollars in surgeries and biologics. The *ATG16L1* gene is a particularly important gene for CRISPR targeting because of its role in detecting antigens and the inflammatory immune

response. We would theoretically test this method on the 10-30% of people who don't respond to Infliximab and those within this group who are in the first two phases of the disease's progression: clinical and biochemical remission. Within the CRISPR/Cas 9 method, I selected 5 possible target sequences out of 157, and within these 5, I ranked them based on their efficiency. The final selection was Rank 39. Using this target sequence, an sgRNA can be designed, which guides the Cas 9 molecule to the editing site.

Limitations

Naturally, this treatment plan does have a few limitations. For instance, extensive research must be done to test the treatment in vitro and in vivo before moving to clinical trials in patients. This would require an extensive amount of funding and resources, which may pose a challenge given the difficulty of the treatment implementation. Additionally, potential side effects such as off-target effects can be damaging and lead to more harm in the gut. This could trigger immune responses and increase the risks of cancer due to uncontrolled DNA modifications. If the treatment is designed with these limitations and the selection of the target sequence in mind, it is likely that it can be effective and help patients.

Next Steps

This project aims to serve as a guide for future experiments in developing a potential cure for Crohn's Disease. In the future, I may utilize this project as an outline for further testing of this method. We can even attempt to expand the population pool and shift our focus to patients who have already received surgery instead of those who haven't reached that point in their disease. This design may serve as a basis for future translational studies testing whether gene correction restores Infliximab responsiveness, or similar. Additionally, we may be able to properly test sequence Rank 39 (efficiency 74.00%, GC Content 40%, no self-complementary strands, 7 MM3s) or the other top four sequences.

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