Exercise as a Means Against Stress-Induced Memory Impairment in Students

Elliott Loo

Abstract

Stress-induced memory impairment is a prevalent issue among students, impacting academic performance and cognitive well-being. There is a negative impact of stress hormones, primarily glucocorticoids, on memory processes such as encoding and retrieval. In contrast, aerobic exercise mitigates stress levels and promotes memory function by increasing hippocampal neurogenesis and brain-derived neurotrophic factor (BDNF) concentration. This paper presents evidence from numerous studies on rats and humans to demonstrate the benefits of exercise on reducing stress and enhancing memory, both of which are crucial for academic success. I found that given the busy schedules of students, regular exercise is a practical and efficient method to combat the harmful effects of stress on memory. Further research should identify specific types and durations of exercise to optimize cognitive benefits for students.

Introduction

Every year during exam season, if asked how they are feeling, most teenagers would reply: I am stressed. According to the American Institute of Stress, in 2024 nearly half of teenage students report feeling significant daily stress, and approximately 18.2% of teenagers experience anxiety-related disorders due to extreme stress.[1] The school and classroom environment, with graded exams, deadlines, and performance pressures, can be major contributors.

Stress, defined as a state of worry triggered by psychosocial and environmental factors, such as taking a test or arguing with a friend, induces a hyperarousal state known as the fight-or-flight response. [2] It is well-known that stress disrupts emotional well-being and impairs healthy memory function, a crucial factor to academic success.[3] The hormones released due to excess stress impact the brain's limbic structure, consequently reducing memory formation and recall.[4] Therefore, it is important for students to utilize strategies, such as exercise, to reduce stress.[5]

In contrast to stress's detrimental effects, aerobic exercise improves memory function by increasing hippocampal volume.[6] In addition, exercise decreases stress levels by enhancing brain-derived neurotrophic factor (BDNF) concentration, brain blood flow, and hippocampal neurogenesis.[7] The numerous positive benefits of exercise, combined with its practicality, make it an optimal solution to alleviate stress in individuals with demanding schedules. Unfortunately, the Centers for Disease Control and Prevention reported that only 23.2% of highschoolers meet the recommended 60 minutes of physical activity per day.[8] The purpose of this review paper is to emphasize how exercise can be used as a tool to reduce stress and improve memory, thereby protecting academic performance in adolescents.

Discussion

1. Stress Negatively Impacts Memory

Memory involves storing and retrieving information in our brain through encoding, a process where neurons are altered and new connections are formed.[9] After the initial encoding, memories are transformed by the strengthening of neurological traces linked with that memory and associated neurological tracts.[9] The two main functions of memory are short-term and long-term memory, distinguished by duration and capacity.[10] Opposed to long-term memory, short-term memory storage is greatly limited, and can only hold information for small periods of time (Figure 1).

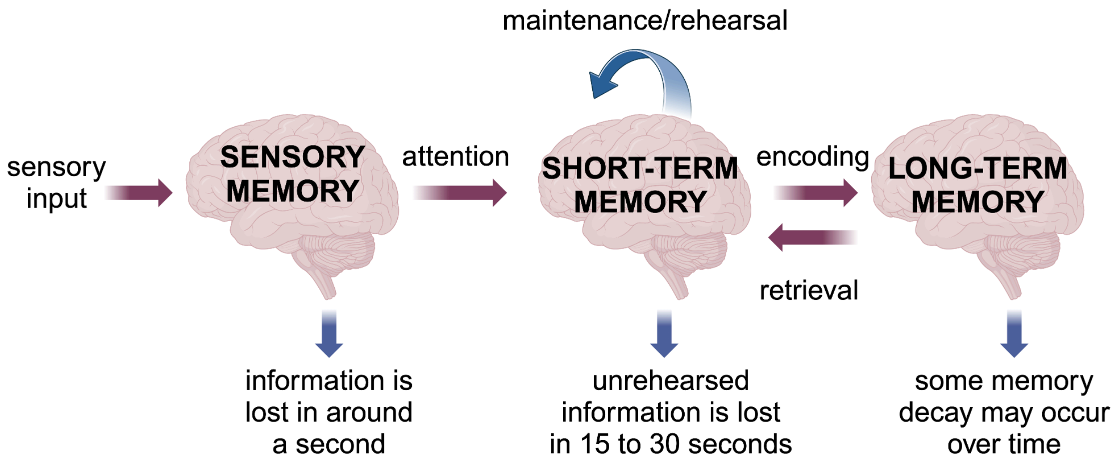

Figure 1: Model of memory processing.

Stress hormones disrupt both the short-term and long-term memory formation and retrieval process.[11] These hormones activate the limbic system in order to reinstate endocrine homeostasis and protect individuals in the long run. There are two components of the limbic system that respond to increases in stress: the sympathetic nervous system (SNS), leading to the immediate release of catecholamines like epinephrine, and the hypothalamus-pituitary-adrenal (HPA) axis, which releases glucocorticoids like cortisol.[12] While catecholamines may aid information storage, glucocorticoids can hinder it (Figure 2).[13] Understanding the relationship between these chemicals and memory function reveals the psychological impact of stress.

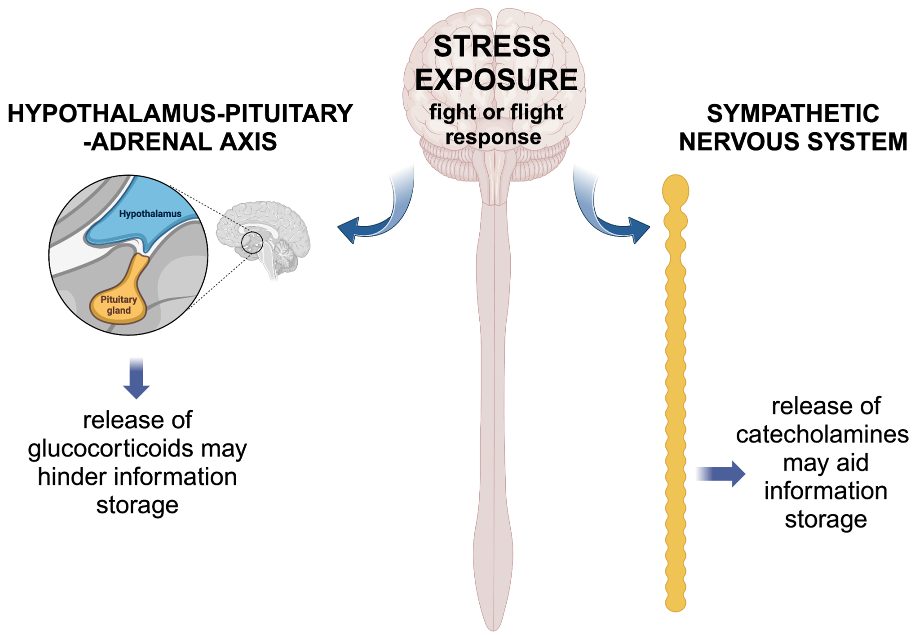

Figure 2: Hormonal stress response.

1.1. The Negative Effect of Stress on Memory Encoding and Storage

Studies in both rodents and humans demonstrate the detrimental effects of stress-related hormones on memory. In rats, long-term exposure to high glucocorticoid levels has been linked to reduced memory function[14] and hippocampal atrophy.[15] Hippocampal damage results in memory dysfunction due to its role in encoding and retrieving information. In humans, similar long-term, elevated exposure to glucocorticoids has been associated with decreased hippocampal volume and impaired performance on hippocampal-dependent tasks.[16] For instance, researchers evaluated participants' encoding and retrieval of words following exposure to the Trier Social Stress Test and found that increased cortisol levels were related to decreased memory function.[17]

Timing is also a significant factor in stress's role in memory storage or encoding. When stress is experienced before learning, it can interfere with the brain's ability to encode new information successfully.[18] This is thought to be explained by decreased neural excitability in the hippocampus long after stress exposure, presumably damaging later memory formation.[19] For example, a study on chronic stress and short-term memory found that individuals who experienced daily stress completed short-term memory-scanning tasks slower than low-stress subjects.[20]

1.2. Temporal Effects of Stress on Long-Term Memory Retrieval

Importantly, stress affects not only the acquisition and retrieval of new, short-term information, but also long-term memory retrieval.[13] A meta-analysis of 16 placebo-controlled studies evaluating the effects of cortisol administration on memory found that cortisol treatment had an overall negative impact on memory retrieval.[21] Still, there is a temporal significance between stress exposure and memory retrieval. This was examined in a study on the impact of glucocorticoids on long-term spatial memory of prior-learning in rats.[22] The researchers monitored the performance of rats previously trained in a water-maze spatial task and found that rats exposed to stressors 30 minutes before the task had impaired memory function. In contrast, rats exposed 2 minutes or 4 hours prior exhibited no impairment. Notably, the rats with impaired recall function had higher amounts of glucocorticoids in their system throughout testing. These findings suggest that stress is most harmful when glucocorticoid levels have time to peak, but not decrease.

A review on hormonal responses to stress found that glucocorticoid concentrations begin to change around ten minutes after stress exposure.[23] Specifically, the stress response impairs memory retrieval over 20 minutes after the stressor.[11] In line with the aforementioned study on rats, humans who experienced stress 25 minutes before a memory recall test exhibited impaired memory function compared to a control group.[24] Those in the stress group still had weakened memory recall during testing 90 minutes after stress exposure, despite recovered cortisol levels. It is important to note how stress harms memory in humans even a few hours after exposure. Understanding the timing of stressful events and their impact on memory retrieval is important for developing strategies to reduce stress' negative impact on memory. As discussed in a section below, exercise is a promising tool for alleviating these effects.

1.3. Effect of Stress on Memory and Performance in Students

Stress and its impact on academic performance is a delicate balance; optimal stress levels magnify learning,[25] but excess amounts of stress hinder the learning process.[26] Unfortunately, students are prone to heightened stress levels because of the intense demands and pressures of school. Stress around the time of learning enhances memory function for new information since the stress reactions block out any encoding of irrelevant material.[27] For instance, humans who endured psychosocial stress directly before learning stressor-related and neutral words, recalled more stressor-related words than the controls did during a retention test.[28] In essence, stress can strengthen memories formed during the stressful event. Often students procrastinate, inducing stress, which then reinforces memories formed during last-minute studying, known as cramming.[29] However, while cramming the night before a test may be beneficial in the short-term, it prevents effective information consolidation, decreasing memory functionality in the long-term.

Medical school is a pertinent example of where stress is a prevalent issue in an academic setting. This is due to the abundance of information required to learn, along with the competitive environment. An analysis of surveys and interviews with first-year medical students revealed moderate negative and significant connections between academic performance and stress sources, and stress levels.[30] Greater stress contributes to decreased academic achievement. Similarly, a literature review on stress in Chinese adolescents reveals a negative correlation between student's academic stress and academic achievement.[31] China's culture is extremely school-focused and as a result, academic stress is a primary stressor in Chinese adolescents.[32] This is evident in a study where 686 Chinese middle schoolers were interviewed about stressors including teacher punishments, class rankings, and academic failure, and their answers were compared to their standardized test scores.[33] The results indicate that greater stress levels are correlated with lower academic achievement. While there are contradictory findings, researchers suggest that the harmful consequences of stress outweigh the benefits in academic settings.

2. Exercise as a Stress-reductive Tool to Improve Memory

2.1. Exercise Benefits Stress Regulation

Exercise is an effective mechanism to decrease stress' impact on the body.[34] During stressful situations, the HPA axis and SNS are activated.[35] In the case of psychological stress, the energy created from the hyperarousal state remains in the body. In other words, physiological stress is outwardly manifested, while psychological stress is intangible. To adjust to stress, the body undergoes allostasis, which allows it to maintain stability. However, repeated cycles of allostasis, called allostatic load, overactivate the stress system which increases the long-term risk of chronic disease (Figure 3).[36]

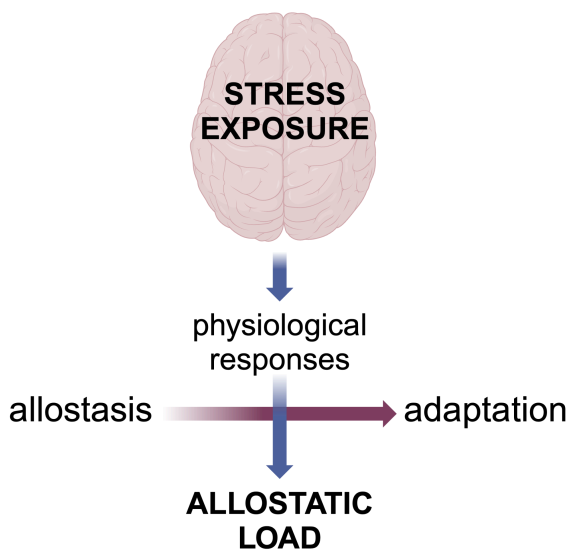

Figure 3: Development of allostatic load.

A solution to reduce allostatic load is physical activity. For instance, a study on exercise's protective role on stress system dysregulation concluded that the risk of the prolonged allostatic state, resulting in illness, is determined by mental and physical fitness.[37] The researchers assert that while a combination of stress-mediated allostatic load and lack of exercise increases the risk for mental and physical illness, constant exercise decreases the consequences of allostatic load. Simply put, exercise reduces stress. To explain the biological underpinnings of this outcome, a review on exercise's impact on the brain outlines stress-reducing benefits of exercise.[7] The authors describe how aerobic exercise enhances cognition and bodily functions by increasing blood flow to the brain, promoting neurogenesis in the hippocampus, and increasing levels of brain-derived neurotrophic factors (BDNF), which stimulates mood regulation. In essence, exercise regulates the body's resilience to stress by decreasing allostatic load and improving brain function.

2.2. Opposite Effects of Exercise and Stress on Hippocampal Neurogenesis.

The hippocampus is a region in the brain that is not only involved with mood regulation and memory but is also sensitive to and manages the brain's stress response.[38] New evidence suggests that stress suppresses hippocampal neurogenesis by activating the HPA axis and glucocorticoid receptor.[39] In contrast, studies on hippocampal neurogenesis in rodents showed that antidepressants and exercise block the negative effects of stress.[38] During exercise, certain molecules such as serotonin and norepinephrine are secreted which promote hippocampal neurogenesis.[40] In addition, many rat experiments that limit physical activity such as physical restraint,[41] immobilization,[42] and foot shock,[42,43] all impair neurogenesis. Combining these studies supports that by increasing hippocampal neurogenesis, exercise acts as a counterplayer to stress-induced neurodegeneration.

2.3. Opposite Effects of Exercise and Stress on BDNF Concentration

A critical factor in neurogenesis is BDNF concentration, which is associated with the serotonin system to regulate positive emotions and memory.[44] While chronic stress leads to cell loss in the hippocampus, BDNF differentiates and preserves these neurons, and regulates synaptic plasticity.[45] Neuroplasticity is the brain's ability to rewire and adapt, on a molecular level, in response to stimuli.[46] Stress, an intense external stimulus, leads to various neuroplastic changes. However, excess stress decreases BDNF levels[47] and alters synaptic plasticity, harming the hippocampus' ability to reduce stress levels.[48] While it is uncertain how permanent these damages are, stress clearly threatens the limbic system's functionality.

Exercise increases BDNF levels and serotonin metabolism in the prefrontal cortex and hippocampus,[7] therefore reducing stress and improving mood, memory and learning.[49] This concept was also identified in a study evaluating the relationship between aerobic exercise and its neural correlates.[50] Following one bout of aerobic exercise, the serum BDNF concentration in young adult male participants increased. These results were associated with an improved cognitive performance of the face-name task. By amplifying BDNF concentration, exercise not only protects the hippocampus from stress-induced damages, but enhances stress regulation, cognitive wellbeing, and memory.

2.4. Overview of Exercise's Benefit on Memory Across Ages

Overall, physical activity provides many cognitive benefits, especially with regard to memory. In the past three decades, research on the relationship between exercise and memory has grown, particularly in relation to its positive effect on long-term memory. For example, a meta-analysis reviewed the mnemonic effects of one bout of aerobic exercise in 22 experiments and a chronic exercise intervention in 19 experiments.[51] Results identified a small-moderate effect in acute interventions and a small effect in long-term interventions. It is important to note that the magnitude of these significant findings changed slightly when short-term and long-term memory were evaluated separately. Likewise, a meta-analysis evaluated 42 experiments testing the effects of acute bouts of exercise on episodic memory function (frontiers). Researchers found that exercise prior to encoding improved free-recall, exercise following encoding improved memory recognition, and exercise during had no effect. The review reveals age, exercise type, and test timing as crucial factors in exercise's influence on episodic memory.

A systematic review on the effect of physical activity on children's memory discovered that physical activity enhances certain features of long-term episodic memory.[52] The authors analyzed 14 studies and determined that physical activity improves free-recall, cued-recall, and had no impact on memory recognition. Similarly, a systematic review of 17 studies on the impact of exercise on young to middle-aged adults found a majority of the trials to reveal that acute and chronic exercise improved memory function.[53] The results highlight the emerging significance for further research on the cognitive benefits of exercise in this age group. Collectively, these reviews underscore the importance of exercise for all ages to improve memory function and overall brain health.

2.5. Exercise Interventions Benefit Animal Memory

According to a mouse study on the influence of physical activity on memory, 14 days of wheel running enhanced memory acquisition and retention.[54] To distinguish memory formation from memory retention, the researchers presented different groups of mice with the running wheel either before or after a spatial Y-maze test. The data showed that exercise significantly increased the number of mature neurons, suggesting that exercise-induced neurogenesis positively impacted Y-maze performance. However, certain studies contradict this claim. For example, an experiment that trained selective breeds of mice to wheel run at high levels concluded that an increase in neurogenesis had no effect on learning the Morris Water maze.[55] These findings conclude that while exercise promotes neurogenesis and certain types of memory, its impact on overall memory and learning may vary depending on the cognitive task at hand and surrounding conditions.

Still, an examination of neurogenesis inhibition tested rats in a Morris water maze and displayed a negative impact on long-term memory, supporting the initial claim that neurogenesis enhances memory functions.[56] Similarly, an investigation of the cognitive impact of voluntary wheel running on young mice strengthens this theory. Results displayed that mice housed with a running wheel not only had an increase in neurogenesis but improved retention and quicker acquisition than mice housed without a wheel, allowing them to complete a Morris water maze faster.[57] Additionally, the impact of exercise on memory retention may vary depending on the amount of exercise. An examination of voluntary exercise on memory processes in rats revealed that the retention of object recognition in low-running groups was promoted, while in high-running groups it was impaired.[58] These contradictions indicate that the intensity or modality of exercise may limit or magnify the resulting memory changes.

2.6. Exercise Interventions Benefit Human Memory

In relation to the animal studies above, the following studies reinforce these findings in human subjects. Magnetic resonance imaging was conducted on two groups of 60 adults who afterward either engaged in aerobic exercise or stretching for six months.[6] Short-term spatial memory was analyzed at baseline and at intervention completion and six months after that. Findings indicate that exercise intervention increases hippocampal volume and BDNF levels in serum. However, only increased hippocampal volume was associated with increased spatial memory function. Similarly, an aerobic exercise experiment including 28 young adults demonstrated that after six weeks, a consistent running schedule improved their visuospatial memory.[59] The results in these short-term memory studies parallel those in long-term memory. For example, an acute exercise study in 48 adults used the paragraph recall method to determine that acute exercise increased long-term memory retention compared to the no-exercise control group.[60] In general, exercise has a prominent role in improving memory function by altering brain structures such as the hippocampus. Moreover, exercise promotes cortical volume maintenance,[61] protecting cognitive well-being.

Conclusion

Research on both rodents and humans indicates that glucocorticoids have harmful impacts on memory. Long-term exposure to high glucocorticoid levels in rats has been linked to reduced memory function and hippocampal atrophy.[14,15] In humans, similar exposure has been associated with decreased hippocampal volume and impaired performance on hippocampal-dependent tasks.[16]

Importantly, stress affects not only the acquisition and retrieval of new information but also long-term spatial memory retrieval.[22] In the academic context, stress can either enhance or impair memory depending on its timing relative to learning.[18,27] While stress during learning may improve short-term memory for stressor-related material, it can hinder long-term memory formation.[19] Additionally, stress experienced shortly before retrieval can impair memory recall, even after cortisol levels return to normal.[24] Indeed, studies of medical students and Chinese adolescents reveals a negative correlation between academic stress and academic achievement,[30,31] highlighting the potential consequences of stress on academic performance.

Numerous studies suggest a positive relationship between exercise and memory. A meta-analysis found a small to moderate effect of acute exercise on memory and a small effect of chronic exercise.[51] Research in both rodents and humans supports the role of exercise-induced neurogenesis and increased BDNF concentration in improving memory acquisition and retention.[6,54] Exercise has also been shown to enhance visuospatial memory[59] and long-term memory retention.[60]

The research presented here highlights the detrimental effects of stress on memory and the potential of exercise to mitigate these effects. Given the prevalence of stress in academic settings, particularly among adolescents, promoting regular exercise could be a practical and effective strategy to protect memory function and academic performance. By prioritizing physical activity, educational institutions can create healthier and more productive learning environments. Future research should investigate the optimal types and durations of exercise for stress reduction and memory improvement in students. Additionally, there is a need for researchers to continue exploring the relationship between these variables specifically in adolescents and children.

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