THE EFFECTS OF AN ACUTE BOUT OF PHYSICAL ACTIVITY ON YOUNG ADULTS' ATTENTION, EPISODIC, AND OBJECT LOCATION MEMORY

By

AHMED S. QAZI

(Under the direction of Dr. Phillip D. Tomporowski)

ABSTRACT

The present dissertation is aimed to determine whether an acute bout of moderate intensity physical activity improves young adults' attention, episodic, and object location memory. This dissertation is also aimed to determine if attention mediates the relationship between physical activity and long-term memory. Finally, this dissertation is aimed at elucidating the mechanisms by which the complexity of physical activity influences learning.

The first phase of the present dissertation, a systematic review and meta-analysis provided novel evidence that exercise before encoding improved memory, affecting free-recall memory more so than recognition and cued-recall memory. Exercise after encoding improved memory as well, affecting recognition memory more so than free-recall and cued-recall memory. Exercise during encoding did not influence memory. Therefore, these findings led to the second experiment that examined the effects of an acute bout of physical activity occurring prior to encoding on attention and long-term episodic memory.

The second phase of the present dissertation, a randomized, controlled trial, sought to assess the effect of an acute bout of physical activity on young adults' attention and long-term episodic memory (assessed via free-recall, recognition, and object location memory tests). A sample of 60 college-aged students ($M_{age} = 20.25 \pm 1.73 \text{ years}; \text{male} = 21, \text{female} = 39$) were randomly assigned to one of three groups; simple physical activity, complex physical activity, or control and engaged in either a 15-minutes physical activity protocol or seated rest. Participants were then assessed on tests of attention and long-term memory. The long-term memory test was administered immediately, 24-hours, and 7-days after encoding. Analyses for free-recall memory revealed a main effect for Group, $F(2, 57) = 8.785$, $p < 0.05$, $\eta_p^2 = 0.236$, and Time, $F(1.82, 57) = 6.645$, $p < 0.05$, $\eta_p^2 = 0.104$. Participants who completed a complex bout of physical activity demonstrated greater and more durable free-recall memory compared to simple and control conditions. All other results were non-significant. In conclusion, with respect to free-recall memory, performing mentally engaging acute bouts of physical activity prior to learning novel material results in the least amount of information decayed across time.

INDEX WORDS: long-term memory, episodic memory, attention, free-recall, recognition, object-location

THE EFFECTS OF AN ACUTE BOUT OF PHYSICAL ACTIVITY ON YOUNG ADULTS' ATTENTION, EPISODIC, AND OBJECT LOCATION MEMORY

by

AHMED S. QAZI

B.S., Augusta University, United States, 2015

M.S., Augusta University, United States, 2017

A Dissertation Submitted to the Graduate Faculty of The University of Georgia in Partial Fulfillment of the Requirements for the Degree

DOCTOR OF PHILOSOPHY

ATHENS, GEORGIA

2024

THE EFFECTS OF AN ACUTE BOUT OF PHYSICAL ACTIVITY ON YOUNG ADULTS' ATTENTION, EPISODIC, AND OBJECT LOCATION MEMORY

By

AHMED S. QAZI

Major Professor:	Phillip D. Tomporowski
Committee:	Patrick J. O'Connor Sami Yli-Piipari

Electronic Version Approved:

Ron Walcott
Dean of the Graduate School
The University of Georgia
December 2024

DEDICATION

All praise be to the Almighty Allah (SWT), the most beneficent, the most merciful, who blessed me endlessly with the will to fulfill this task

ACKNOWLEDGEMENTS

Completing my dissertation has been one of the biggest accomplishment of my life and would not have been possible without the utmost support from my family. First and foremost, I would like to express my deepest gratitude to my wife Sumayyah, who stood by my side during the most difficult times of my life. Without her constant love, support, and motivation, I would not be where I am today. I would also like to express my sincerest gratitude to Mama, Baba, Appa, and Luna. You all have contributed immensely to my success and your sacrifices, dedication, and endless love have led me to become the man that I am today.

Secondly, I would like to thank my major professor, Dr. Phillip D. Tomporowski. It was an honor for me to be your graduate student and train under your mentorship. You have truly inspired me to become not only a better academic, but a better man. Your passion and dedication to academia, your passion and care for your students, and your passion and love for your family has inspired me immensely. Thank you for not giving up on me and for the profound impact that you made on my life.

Thirdly, I would like to express my utmost gratitude to my dissertation committee members, Dr. Patrick O' Connor and Dr. Sami Yli-Piipari. Your wisdom, knowledge, and guidance over the last five years sincerely enhanced the quality of my studies. I enjoyed your mentorship, and I cannot thank you enough for serving on my committee.

Fourthly, I would like to thank Dr. Stephanie Sullivan for taking me under her wing and putting her trust in me to complete my dissertation. Her constant encouragement and patience have made a profound impact on me.

Lastly, I would like to thank each and every member of the Cognition and Skill Acquisition lab whom I got the chance to work with over the last five years. You all made my time at the University of Georgia very enjoyable, and I will cherish the relationships that I built with you forever.

TABLE OF CONTENTS

Page

CHAPTER

LIST OF TABLES

Page

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

Contemporary psychologists use the term ‘cognition’ as a general term to quantify the processes that reflect individuals’ knowledge or awareness, including judgement and reasoning , (Buckworth et al., 2013). Cognition is assumed to operate in a complex, hierarchical fashion with higher and lower order processes that include goal-directed actions as well as unconscious, automatic, and reflexive behaviors.

Interest in human cognition can be traced back to the third century BCE, when philosophers such as Aristotle expressed an early interest in the human mind. Aristotle’s observations suggested to him that the workings of the human mind and mental processes could be studied as operation that could be explored systematically (Hergenhahn, 2008). Later philosophers, such as Rene Descartes, maintained the assumption that cognition could be measured via direct observation and measurements. This empirical approach to the study of the mind continues today and underscores approaches to study the constructs of attention and memory.

References

Buckworth, J., Dishman, R. K., O’Connor, P. J., & Tomporowski, P. D. (2013). *Exercise psychology, 2nd ed* (pp. xv, 527). Human Kinetics. https://doi.org/10.5040/9781492595502

Hergenhahn, B. R. (2008). *An Introduction to the History of Psychology*. Cengage Learning.

CHAPTER 2

LITERATURE REVIEW

This chapter introduces the psychological constructs of attention and memory. First, I provide a detailed theoretical framework for attention, followed by the neurobiology of attention. Second, I review the literature on the effects of exercise on exercise on attention. Third, I present theories of memory they pertain to the subsequent chapters, followed by the neurobiology of memory. Finally, I review the literature on the relationship between exercise and memory.

2.1 Theories of Attention

The psychological construct of attention has remained a central topic of interest among historical and contemporary researchers. Attention stems from Latin *attendere*, meaning "to heed." Though the roots of attention stem from time of the Roman empire, there is no reference to human capacity until Descartes in 1649 connected attention to the movement of the pineal body which acted upon the spirit (Itti et al., 2005). The approach of the early 20th century functional psychologists was influenced by the views of experimental psychologist William James, who summarized attention as "focalization and concentration of consciousness." James emphasized that attention consisted of taking possession of the mind, focusing on one out of several streams of thoughts. He highlighted the idea of focalization and concentration which resulted in an individual's withdrawal from some streams and more effective focus on other streams (Schmidt & Lee, 2011). For James, a focalized stream of consciousness consisted of an everchanging, continuous, and functional phenomena. The collective effects of attention therefore could allow the self to perceive, distinguish, and remember ideas better than otherwise possible (Andrade & Walker, 2020). During the beginning of 20th century, the study of underwent a vast transformation, transitioning from a philosophical to an experimental approach. With a renewed interest in mental processes during this time, a contemporary notion of attention was developed and has since become a multifaceted definition grounded with theoretical and neurobiological explanations.

Following the work of James and other 29th century psychologists, theorists posited that attention could be quantified in terms of capacity and allocation as the degree of interference between two tasks of attention defined the construct as the degree of interference between two tasks. Single channel theories hypothesized that attention consisted of a fixed capacity for information processing and that performance on a given task would deteriorate if this capacity was reached or exceeded. These single-channel theories viewed attention as a unitary process or resource that could only be directed at a singular processing operation at a time (Schmidt & Lee, 2011). English psychologist Alan Travis Welford proposed that all processes required attention such that the ‘self’ would be regarded as a channel that can only be occupied by one operation at a time. Welford’s theory was in line with sequential processing, which explained that the individual could only attend to a single stimulus at a given time. The single channel theory also hypothesizes that information processing is universally attention demanding, therefore unconscious, automatic processing is not possible (Schmidt et al., 2018). Research findings demonstrated that attention was unnecessary during the early stages of information processing but would be required during the later stages. D.E. Broadbent’s proposed a filter theory of attention that hypothesized a ‘bottleneck’ just before the perceptual analysis stage of the information processing model (contemporarily known as response programming) (Broadbent, 1958) (*Figure 2.1*). Due to the presence of the bottleneck, only one stimulus can be perceived at time. If two stimuli are presented simultaneously, one piece is processed immediately whereas sensory information for the second stimulus is held briefly as unanalyzed information. Based on this model, the individual can only process the second stimulus once the first stimulus has been completely processed (Kahneman, 1973).

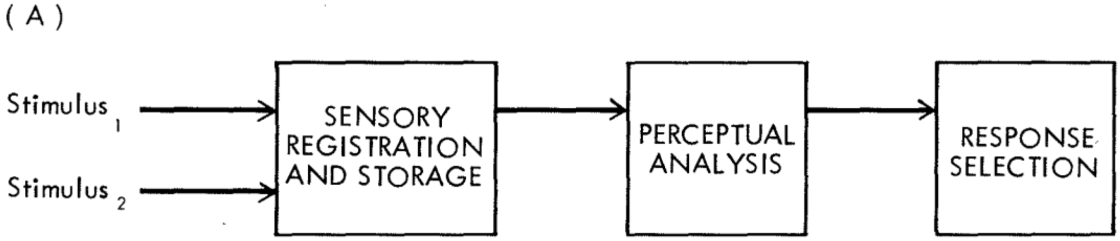


Figure 2.1. Broadbent’s Filter Theory (from Attention and Effort by Daniel Kahneman)

The filter theory hypothesized three elements: a short-term store (S-system), a selective filter, and a limited capacity channel (P-system). Multiple streams of information enter the model via the S-system in parallel where they are analyzed for physical descriptive features. The selective filter can then be set and defined as a particular characteristic (e.g. pitch, color, size, etc.) of the stimulus. The selective filter then allows those stimuli that adhere to the classification to enter into the P-system. The P-system carries out additional perceptual analyses of the accepted stimuli. Once processing is complete, the selective filter allows a new stimulus to enter. Due to the P-systems inability to process information in parallel, the filter theory posits that attention cannot be divided and therefore may only be selective (Kahneman, 1973).

Selective attention may either be intentional or incidental. Intentional selection occurs when an individual consciously and purposely choses to attend to a source of information while concurrently inhibiting attention to other sources. Conversely, incidental selection occurs as an involuntary or unconscious response to an external stimulus (Schmidt et al., 2018). Broadbent’s filter theory would eventually be refuted given that parallel processing of simultaneous stimuli does occur via divided attention, or the ability to integrate and process multiple streams of stimuli in parallel (Itti et al., 2005). Divided attention can also be dependent upon effort. Whether or not multiple stimuli can be processed at once depends on the amount of effort and cognitive resources that are demanded by the processes. Humans possess a limitation in the capacity of cognitive resources that are available to handle and process contextual and environmental information (Kahneman, 1973; Schmidt et al., 2018).

Capacity theories of attention have long provided evidence to counter filter theories by arguing against a bottleneck for attention. The capacity theory assumes that humans have a capacity to perform mental tasks, and mental effort is exerted based on the demands of the tasks. Due to the limitation of resources that is present, Daniel Kahneman argued that attention is also a general-purpose limited resource (Itti et al., 2005; Kahneman, 1973). In his capacity theory, Kahneman presents two central elements that explain how resources can be allocated to demands. The allocation policy selects activities for which the governor system causes capacity (or effort) to be provided. Kahneman's capacity theory presents three central questions that must be considered: 1) What factors control the total amount capacity that is available at a given time? 2) What factors contribute to the total amount of attentional capacity that is available at any time? 3) What are the rules of the allocation policy? The allocation policy is controlled by four factors. The first factor reflects the rules for involuntary attention. The second factor reflects momentary intentions. The third factor reflects the evaluation of demands, such that when two tasks require more capacity than is available, only one of the tasks will be completed. The fourth factor reflects the effects of arousal (Kahneman, 1973). Figure 2.2 depicts the capacity model for attention.

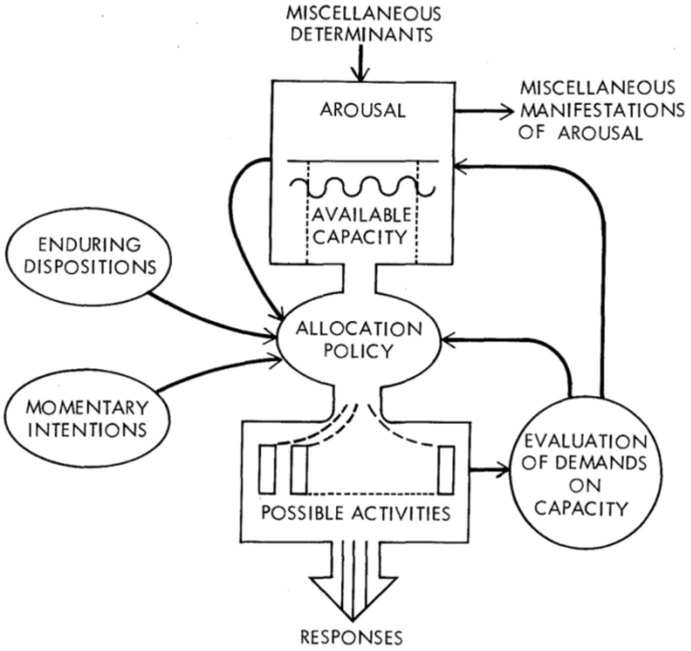


Figure 2.2: The capacity model for attention from (Kahneman, 1973)

2.2 Neurobiology of Attention

Similar to the theoretical explanations of attention, neurobiologists have also attempted to explain attention via an alternative scope. The neural mechanisms underlying attention have long been of interest to a multitude of disciplines. The search for the biological foundations of behavior has been a recurring theme throughout the history of psychology. Influential psychobiologist Donald Hebb provided much of the early work that in part explained perception and learning. Hebb advanced Ivan Pavlov's concept of classical conditioning by integrating it with a neuropsychological theory. Pavlov suggested via his work with animals that repeated experiences led to alterations of neural tracks in the cortex of the brain that in turn led to the formation of memory traces. Hebb suggested a more precise neurobiological hypothesis to explain how the process of associative learning occurred in animals. Hebb posited that behaviors shaped changes at the neuronal level of brain cells. Initially weak neural associations between synaptic cells were strengthened as a result of repeated exposures to stimuli. This Hebbian theory postulates that the process of learning occurs in three stages as a result of neurophysiological changes (Tomporowski et al., 2015). The first stage consists of synaptic changes that occur at the molecular level. The second stage consists of the formation of "cell assemblies," or a system of neurons and the associated pathways connecting them. The third stage consists of the formation of a "phase sequence," or a series of cell assemblies that constitutes a "thought process." (Langille & Brown, 2018). Much of Hebb's contributions bridged the gap between psychology and neurobiology via a network approach. Contemporary researchers have similarly sought to explain attention as a network, countering the early single channel views of attention as a unitary process and thus supporting the notion that it is a multifaceted process (Posner & Rothbart, 2007).

Neurophysiological evidence and neuroimaging data have identified specific brain regions that are responsible for different aspects of attention (Fan et al., 2003, 2005). Specifically, three networks carry out the attentional functions of alerting, orienting, and executive attention (*figure 2.3*). Alerting is defined as achieving and maintaining a physiological state of high sensitivity to incoming stimuli (Posner & Rothbart, 2007). Related to the alerting component of attention is vigilance, or the ability to sustain attention towards specific stimuli (Lindsay, 2020). The alerting network has been associated with thalamic regions, as well. As frontal and parietal regions of the cortex. The primary anatomical structures associated with alerting include the locus coeruleus, right frontal cortex, and parietal cortex (Posner & Rothbart, 2007). The primary neuromodulator that is associated with varying levels of alertness is norepinephrine (Marrocco & Davidson, 1998). The orienting network consists primarily of aligning attention with an external source of a sensory signal. The visual system is the primary sensory system that orients attention to specific stimuli. The orienting system is associated with the superior parietal lobe, tempo-parietal junction, and the superior colliculus. The primary neuromodulator associated with the orienting system is acetylcholine. The executive attention network is involved in error detection and conflict resolution. Brain regions associated with executive attention include the anterior cingulate cortex, lateral ventral cortex, prefrontal cortex, and basal ganglia (Posner & Rothbart, 2007). The prefrontal cortex also combines sensory inputs with past experiences in order to coordinate appropriate responses (Lindsay, 2020).

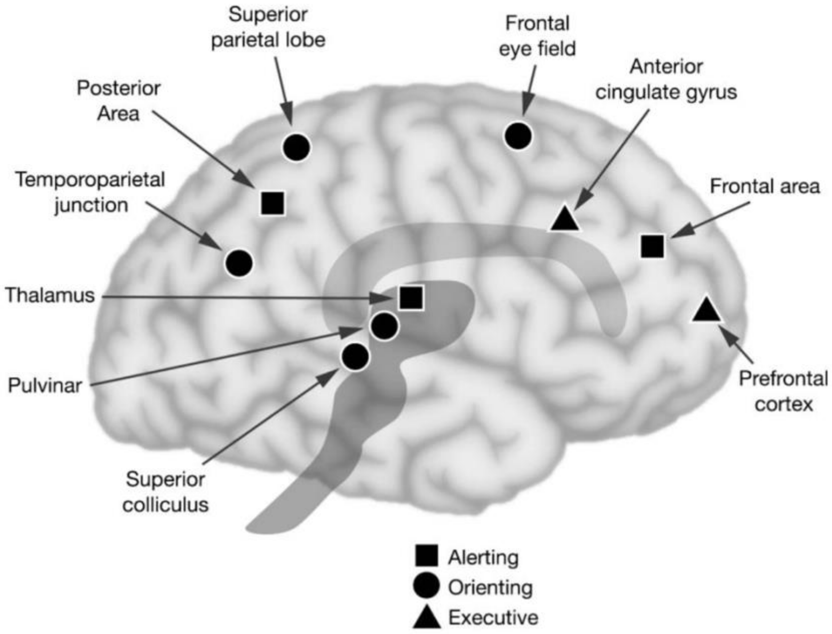


Figure 2.3: Anatomy of the three attentional networks (alerting, orienting, and executive attention) (from Posner & Rothbard, 2007)

These networks play a vital role in the allocation of attention towards necessary demands. Arousal plays a vital role in how attentional resources are allocated. Per the capacity model of attention, a bidirectional model exists between attentional and arousal. When variations in attentional demands occur, there is an associated variation in arousal. Conversely, when there are shifts in arousal, the mechanism by which attention is allocated to different activities is also influenced. The Yerkes-Dodson Law posits that arousal and performance are associated in an inverted-U shape, such that the range between which performance improves with increasing arousal depends on the complexity of the task (Kahneman, 1973). Thus, attentional reserves may not be tapped into to if the task-at-hand is mundane or does not illicit any level of motivation. However, these attentional reserves may be utilized if the task-at-hand is more interesting or induces some degree of motivation. Per the inverted-U hypothesis however, it is evident that more arousal is not always beneficial (*figure 2.4*) (Lindsay, 2020). Increased levels of arousal cause attentional resources to be concentrated on the dominant aspects of the situation, irrelevant of other aspects. Complex tasks therefore require attention to perhaps several varied sources of stimuli and are therefore performed poorly when arousal is elevated. Additionally, a state of high arousal impairs one's ability to discriminate between relevant and irrelevant cues. It is likely that individuals become highly selective when under a state of elevated arousal, but the effectiveness of their selections to attend to deteriorates. Conversely, during a state of low arousal, there may be a failure to adopt to a task which negatively impacts task performance (Kahneman, 1973).

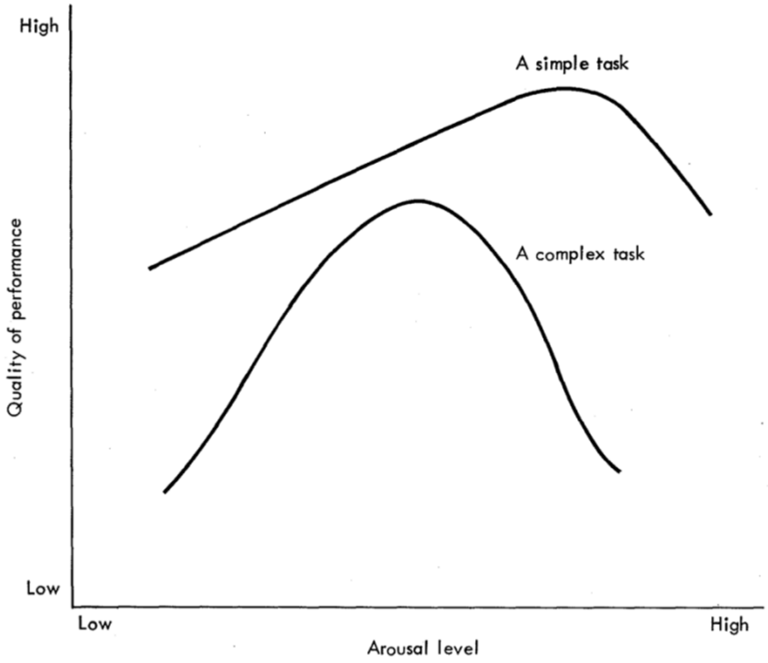


Figure 2.4: The Yerkes-Dodson Law, from (Kahneman, 1973)

The interconnection between arousal and attention has been a central focus among researchers for decades. Exercise induces cascades of physiological responses within the body both at the central and peripheral levels. Exercise-induced changes include increases in core body temperature, heartrate, and blood flow to target muscles, changes in plasma catecholamine concentration, autonomic responses, among others. Such physiological responses have been linked to transient changes in arousal state (Fisher, 2014; Nobrega et al., 2014). According to Yerkes-Dodson's Law, a moderate level of arousal is optimal for performance. Moderate intensity exercise equates to a moderate level of arousal and would therefore produce the most optimal scenario for performance. Acute exercise promotes physiological changes that are also accompanied by biochemical changes both peripherally and centrally (McMorris et al., 2015). These mechanistic changes are directly purported to influence various cognitive components, including attention. During exercise, the hypothalamus and brainstem initiate the activation of the sympathoadrenal system which results in the release of catecholamines. As exercise intensity reaches a moderate threshold, there is also a release of epinephrine and norepinephrine into the bloodstream from the adrenal medulla. If exercise intensity increases to an intense level, there is an associated increase in both plasma epinephrine and norepinephrine. During moderate intensity exercise, there are increases in brain catecholamines which in turn activate the prefrontal cortex, sensory cortices, and their association areas. These exercise-induced changes in arousal lead to enhanced cognitive processing by increasing the signal-to-noise ratio of neurological systems within the brain which in turn enhance attention, stimulus selection, and decision making (McMorris et al., 2015).

2.3 The Effects of Exercise on Attention

The effects of acute exercise on attention have been empirically studied in laboratory settings among both clinical and nonclinical populations. There exists compelling evidence to support that exercise can facilitate attentional processing among children (Samuel et al., 2017) and adolescents (Cooper et al., 2016). Though limited, there is also some evidence to suggest that acute bouts of cardiovascular exercise may facilitate attentional allocation therefore improving overall attention among younger (Hillman et al., 2003) and older (Hsieh et al., 2018) adults. Most of the literature that examines the effects of acute exercise on attention is focused on children. To date, two systematic revies (Janssen et al., 2014; Mahar, 2011) and two meta-analyses (de Greeff et al., 2018a; Infantes-Paniagua et al., 2021) have been conducted to further summarize and quantify the overall effect of acute bouts of physical activity on children's attention. Jansen and colleagues (2014) reported inconclusive evidence for the effects of acute bouts of physical activity on children's attention. This is attributed to the heterogeneity in age and sample size as well as methodological differences among the studies. In contrast, Mahar

(2011) reported direct benefits on attention-to-task behavior as a result of active classroom breaks, therefore implicating the beneficial role of physical activity. Meta-analytic results reported similar inconsistencies. De Greeff et al. (2018) found a positive overall effect of physical activity on attention (g = 0.43), whereas Infantes-Paniagua et al. (2021) reported no significant findings.

With respect to young adults, Chang et al. (2012) conducted a meta-analysis quantifying the effects of acute exercise on cognitive performance, with attention being a primary moderator of interest. The results of the meta-analysis indicated a small positive effect (d = 0.097) of a single bout of exercise on overall cognitive performance. Moreover, significant positive effects (d = 0.416) were also noted for measures of concentration, which were used to quantify attention.

Two meta-analyses conducted with older adults also reported significant effects of exercise on attention. Northey et al. (2018) reported a significant effect of exercise on the attentional domain of cognition. In another meta-analysis of older adults, large effect sizes were reported for auditory (d = 0.52) and visual (d = 0.50) attention. Neuropsychological data is also in line with these findings. Both younger and older adults demonstrate improved exercise-facilitated performance as indicated by the P3 neural marker of attentional control on an attentional Stroop task (Hsieh et al., 2018).

2.4 Theories of Memory

As with attention, the psychological construct of memory has long been of interest to contemporary researchers and psychologists. The philosophical underpinnings of memory date back thousands of years to the time of influential philosophers such as Aristotle and Plato. Historically, the acquisition and transfer of knowledge was a central dogma during the ancient Greek period. Initially, Plato sought to explain how the mind functioned. His early explanation was centered around introspection, or the searching of one's inner experiences. In line with these ideas, Plato's reminiscence theory of knowledge posited that sensory experiences remind the self of what is already known, and that all knowledge comes from remembering experiences that they had prior to entering the body of the self. Plato's nativist ideas stressed the importance of these inborn qualities. Similarly, Aristotle was also interested in explaining the essence of truth in the form of behavior that humans exhibited. However, Aristotle's philosophy was distinct and differed from Plato's (Hergenhahn, 2008).

Aristotle would be one of Plato's most brilliant students and upon Plato's death would go on to continue his ideas. One of Aristotle's early topics was memory, which he discusses in detail in his treatise *On Memory*. In this brief treatise, Aristotle explains memory and recall as the product of sensory perception. He also emphasized mental processes as operations that could be studied empirically. This was in contrast to Plato's nativistic dogma of memory processes. For Aristotle, remembering consisted of a spontaneous trace of something that the self had previously experienced (Hergenhahn, 2008). Contrastingly, Aristotle explained that recall involved a mental search of past experiences. Together, remembering and recall would constitute the laws of association, which for Aristotle explained how memory processes functioned. The most basic of these laws was the law of contiguity, which states that as individuals think of a particular abstract, they also think of an accompanying experience. The law of similarity states that the thought of something particular also initiates the thought of something that is associated with, or similar to it. Conversely, the law of contrast posits that the thought of something also accompanies the thought of that which is opposite to it. The law of frequency, according to Aristotelian philosophy, states that as experiences occur more frequently together, their association will be stronger and therefore provide a stronger memory trace. These laws explaining associationism as developed by Aristotle with influence from Plato would go on to become foundational for understanding how learning occurs (Hergenhahn, 2008). Countless theories have since been developed along with convergent evidence to partially explain how the phenomenon of memory transgresses.

The study of the mind as well as its processes would last across generations. As the discipline of psychology was initiated in Germany in the late 1800s, there resulted a shift towards experimental approaches to quantitively assessing various constructs, particularly memory. Historically over the past two centuries, mammalian memory has been studied via philosophical, psychological, and biological approaches. Herman Ebbinghaus was a German psychologist who centered his research on memory. His early work on memory marked a turning point for psychology as he was the first to study memory experimentally. He was also the first to study memory as it occurred, rather than after it had occurred. To study the phenomenon of leaning as it occurred, Ebbinghaus utilized materials that were novel and had not been experienced previously. He developed a pool of nonsense syllables which he used on himself as a subject to assess the rate of learning. Measuring the amount of information learned across time, Ebbinghaus developed the concept of savings, which he described quantitatively as the amount of information learned. Plotting savings as a function of time, Ebbinghaus created the first retention curve, noting that forgetting was most prevalent during the first few moments after learning and relatively stable thereafter. Further, Ebbinghaus also noted that overlearning, or continuous exposure to already learned material, reduced forgetting considerably (Hergenhahn, 2008). Ebbinghaus's contributions led to an increased interest in cognitive psychology. Over the next 200 years, numerous psychological theories of memory would be proposed to explain how sensory experiences are stored in memory and how stored memories are recalled and retrieved.

The earliest distinction between two unique memory storage processes was proposed by William James who emphasized that the short-term, or “primary” memory is different from long-term, or “secondary” memory. Based purely on introspection, James posited an early theory that qualitatively distinguished between two distinct memory stores. Primary memory according to the James’ theory represents the contents that are active during a given state, such that they are “conscious.” Secondary memory, or memory proper, represents events and thoughts that have been dropped from a conscious state of mind and thus must be brought back into consciousness (Rose et al., 2010). This dual memory storage model was the dominant explanation for the memory storage and retrieval that maintained several memory models including Atkinson and Shiffrin’s model and Baddeley’s working memory model.

Richard Atkinson and Richard Shiffrin proposed a framework that distinguished between short- and long-term memory processes. Three permanent structural features of the memory system were identified as part of this framework; the sensory register, the short-term store, and the long-term store. The role of visual perception and registration of stimuli allows the sensory register to be a distinct component of the human memory system. Visual stimuli leave photographic traces that decay rapidly and are replaced by succeeding streams of additional visual information. The short-term store, otherwise identified as working memory, consists of the temporary storage of information that is longer in duration that the sensory register, but still labile and assumed to decay over time and disappear completely. The short-term store consists of a higher degree of control as opposed to the sensory register. Increasingly abstract coding of information leads to multiple stages of processing that allow for the transfer of information into the long-term store. The long-term store is distinct from the sensory register and the short-term store in that information that is transferred into the long-term store does not decay and becomes lost similarly. Information in the long-term store is relatively permanent. There also exists a clear LTM process for each sensory modality (Atkinson & Shiffrin, 1968; Malmberg et al., 2019). Central to Atkinson and Shiffrin's framework is the transfer of information between the three distinct systems. Importantly, information is copied into alternate systems, and decay within the system according to its decay characteristics. This provides an explanation for how the long-term store is scanned and information is retrieved within the short-term store. The amount of information that is bidirectionally transferred from the short-term store into the long-term store and conversely depends on the individual, as well as control processes including the context of the information. A key control process that is central to the maintenance of information in the short-term store as well as transfer of information into the long-term store is rehearsal. The framework proposed by Atkinson and Shiffrin fractionates the rehearsal buffer into two distinct functions: maintenance and coding. Maintenance utilizes the rehearsal buffer to maximize the raw number of items that are held in the short-term store. Coding signifies that the rehearsal buffer transfers information from the short-term store to the long-term store. Each rehearsal regenerates a short-term store trace which prolongs the decay of information. Only the trace of information that is selected or rehearsed by the individual is strengthened. This transfer of information from the short-term store to the long-term store consists of a combination of automatic, indicating incidental learning, and controlled transfer, indicating elaborative encoding (Atkinson & Shiffrin, 1968; Malmberg et al., 2019). In addition to rehearsal, there are other control processes that are critical to the overall human memory system, including the storage and retrieval of information from the long-term store.

With regard to storage of information in LTM and its necessary retrieval, Atkinson and Shiffrin posited that the primary component of the search process for retrieval consists of locating traces in the long-term store. Further, there may exist more than a single trace for a single item that may be either partial or entirely complete. A partial trace may not result in an exact match, rendering the recall of an item partially unsuccessful. However, a search for a trace that results in a complete match results in successful search procedure. These long-term traces are evolving frequently as new information is continually added to LTM. The complete or partial inability to recall information from LTM may be due to interference and search failure as opposed to decay (Atkinson & Shiffrin, 1968; Malmberg et al., 2019).

An extension of Atkinson and Shiffrin framework further expanded the distinct human memory processes of recall and recognition. The Search of Associative Memory (SAM) theory sought to better explain memory storage mechanisms via the distinct models of interference, forgetting, and repetition. Similar to Atkinson and Shiffrin's original model, the SAM model posits that the short-term store buffer serves as a mechanism for rehearsal processes and information in the long-term store is dependent upon the nature and duration of items in the short-term store. Novel to the SAM was the notion of how retrieval cues are utilized to direct a memory search. The model also assumes that different types of information are stored in the long-term store, including importantly contextual information. The strength of the association between the cues used during a specific memory search and stored memory traces is crucial for an effective match for retrieval of information. The SAM theory further suggests that retrieval of information is a function of the relative and absolute strength of a given target item. The probability of successful retrieval decreases as the number of items to be stored decreases, directly reducing the relative strength of the items. However, as a target item to be remembered is studied for a longer duration, the absolute strength of the item increases. The SAM model also highlights the role of the context in storage and retrieval. The SAM model distinguishes content from context as having differentiable roles. An important characteristic however is whether content and context are stored and retrieved explicitly or implicitly. Context includes information that is not the target material to be encoded and retrieved, often including “background” information that is not experimentally varied or controlled. This information is nonetheless stored and subsequently used as cues for the retrieval of target information, or content. The process of free-recall therefore depends heavily on stored context information as during retrieval of a specific trace not only presents content information but also the stored context information (Malmberg et al., 2019).

Recognition memory was initially explained based on global familiarity, or the summation of the activation across all memory traces. However, a more specified and plausible model was conceived to provide a more detailed explanation for the functionality of recognition memory. The Retrieving Effectively from Memory (REM) model was proposed based on optimal decision making. REM posited that memory trace activation increases when more features match between memory probe and trace and decreases if there is a mismatch. If the trace differs from the probe such that it is for a different item, then mismatching also increases and activation decreases.

Alan Baddeley proposed a working memory model which was more dynamic than short-term memory (STM); the term working implying that that WM could not only store information but this information could also be manipulated during cognitive processes such as comprehension, reading, and learning (Baddeley, 2012; Jonides et al., 2008; Rose et al., 2010). The idea of a “working” memory was developed initially from short-term memory. In his early distinction between short-term memory and working memory, Baddeley implied that short-term memory simply consists of temporarily storing information, whereas working memory consists of storage and manipulation of information. In line with James' dual memory model, Baddeley expanded that the short-term storage system was primarily phonological, whereas the long-term storage system was primarily semantic. Working memory was initially thought of as a unitary store buffer between short-term memory and long-term memory. However, this initial assumption was modified in favor of a multi-store model of working memory consisting of initially of three distinct components; the central executive, phonological loop, and visuo-spatial sketchpad, with the addition of the episodic buffer as part of the updated model (*figure 2.5*) (A. Baddeley, 2012).

The central executive is the most crucial, yet complex component of the working memory model. The central executive is a sort of attentional system that controls the slave systems of the phonological loop and visuo-spatial sketchpad. The central executive regulates the function of these systems and relates them to long-term memory storage. The central executive controls attentional processes because it decides which information to attend to and which component of working memory that information should be allocated to. Unlike the phonological loop and visuo-spatial sketchpad, the central executive does not function as a memory store. Integrating the information from both the phonological loop and the visuo-spatial sketchpad, the central executive is able to rely on long-term memory traces as well (A. Baddeley, 2012). A more recent addition to Baddeley's WM model was the episodic buffer. In his initial model, a buffer that linked working memory to long-term memory was absent. The episodic buffer is a limited capacity storage system that provides a temporary storage of information and is capable of integrating and processing inputs from both working memory processes as well as long-term memory. The episodic buffer is also considered to be a connection between WM and perceptual processes. The visuo-spatial sketchpad is primarily responsible for maintenance of visual and spatial information. The fractionation of visual and spatial short-term memory served as the foundation for the visuo-spatial sketchpad. A slave system beneath the central executive, the visuo-spatial sketchpad is critical for the processing of visual and spatial information. The visuo-spatial sketchpad also manipulates streams of information held in long-term memory, which allows for the recall of visual information that can be conceptualized on the sketchpad. The phonological loop consists of a short-term phonological store and an articulatory control process that deals with spoken and written material. The phonological store temporarily holds information in a speech-like code. Auditory stimuli, or spoken words, can enter the phonological store. The articulatory control process acts as a rehearsal system that repeats information held in the phonological store. This repetitive process allows for the temporary storage of auditory stimuli that can be stored for a brief period and serves as the basis for the comprehension and disposition of spoken material.

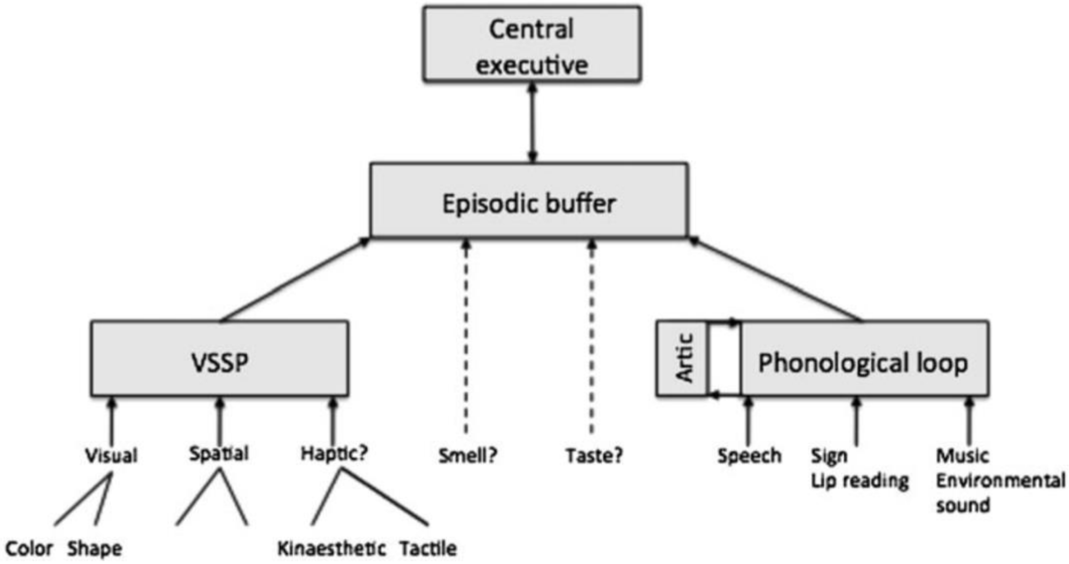


Figure 2.5: Updated WM Model depicting the flow of information from perception to WM, from (Baddeley, 2012)

The views of William James, Alan Baddeley, Richard Atkinson, and Richard Shiffrin collectively categorize short-term, long-term, and working memory into a multistore model of memory. The multistore model of memory represents STM and LTM as architecturally unique components of a system. The unitary-store model by contrast posits that these short- and long-term processes each rely on the same representations. The two processes differ with respect to the level activation of representation and processes that act upon these representations. The unitary store model rejects the assumptions of a multistore model representing distinct memory systems. The unitary store model also theorizes that short- and long-term memory processes are not separable and therefore consist of similar underlying neural systems. A central component of the neural similarities between short- and long-term processes is the medial temporal lobe. Though the medial temporal lobe is particularly implicated in long-term memory activation, there is growing evidence to highlight its relevance to short-term memory activation as well (Ranganath & Blumenfeld, 2005). The unitary-store model also suggests that short-term memory traces consist of temporary long-term memory representations. The most fundamental support for this notion is grounded within Cowan’s model (Cowan, 2001) (*figure 2.6*). According to the model, information stored in long-term memory is representational and can vary based on its strength of activation. Those representations that possess an increased strength of activation are more readily available for retrieval via short-term memory traces. Though these traces are subject to forgetting and interference effects, if they are within the focus of attention, can be readily subject to cognitive activation. An individual’s limited scope of attention can therefore engage with one functional context at a time. Mechanistically, short-term memory therefore can be represented as a long-term memory representation that is within the scope of attention (Jonides et al., 2008).

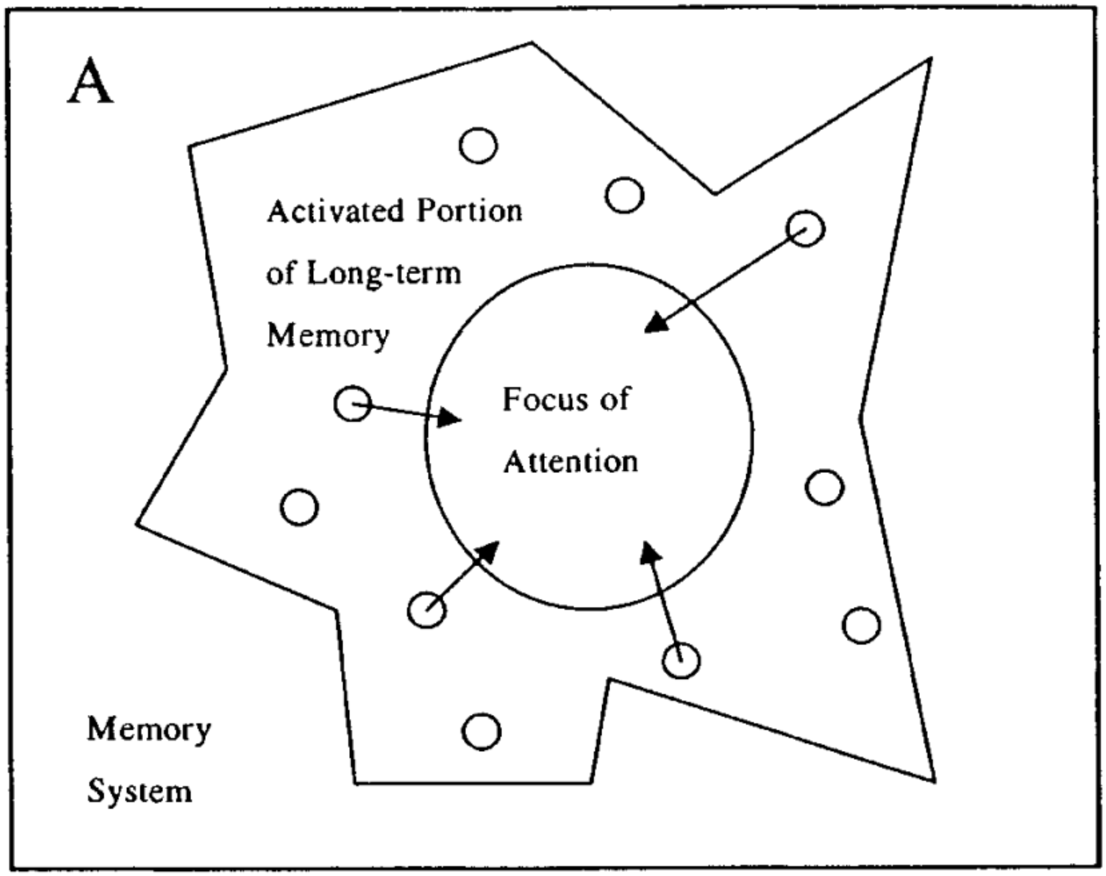


Figure 2.6: Cowan's Model, from (Cowan, 2001)

2.5 Neurobiology of Memory

The theoretical underpinnings of memory processes provide an insight into the complexities of the mammalian memory systems. Converging evidence and the interdisciplinary investigation of human memory systems from biological perspectives have since elucidated mechanisms underlying memory. The neurobiology of memory has been the interest of researchers for decades. The treatment of memory disorders can be dated back to the late 19th century with Ribot's classification of amnesia and other memory disorders due to psychological trauma and neurological injuries (Squire & Wixted, 2011). Following the work of Ribot and beyond, the treatment and study of brain injuries became the primary mechanism for clarification of memory organization. The initial view was that brain injuries of any kind would result in a global impairment affecting the mental and physical capacities of life in some aspect (Squire & Wixted, 2011). However, this notion was countered with the rise of the localizationist view which was supported with evidence by several physiologists. During the early 20th century, the same proposition that brain injuries would result in global decrements was applied to memory. It was implied that memory would be impacted wholly as it was distributed throughout the cortex. The localization view was challenged by the work of Brenda Milner and colleagues after their work with a patient, known as H.M. Milner and colleagues established a fundamental memory principle that memory could be classified as a cerebral function. This principle disentangled memory as a process, distinct from other perceptual and cognitive functions. The work of Milner and colleagues also indicated that some long-term memories were dependent upon the hippocampus and medial temporal lobe (MTL) for their acquisition and subsequent retrieval. Therefore, memory was classified not as a unitary faculty that governed the mind, but rather a composition of several distinct operating systems with individualized neuroanatomical compositions. Subsequent work with animal models of monkeys further classified the entorhinal, perirhinal, and parahippocampal cortices of the parahippocampal gyrus as additional important structures for the formation of memories (Squire & Wixted, 2011). The initial taxonomy of memory split the construct of LTM into declarative (explicit) and nondeclarative (implicit) memories. Declarative memory represents the capacity for the conscious recollection of facts and events, primarily dependent on the medial temporal lobe and diencephalon. Declarative memory allows for the encoding of multiple memories that can associate items and events. Declarative memory can be further classified into semantic memory, which represents general facts about the world, or episodic memory, which represents the conscious recollection of previous experiences specifically associated with the context in which the memory was initially experienced. Nondeclarative memory can be further classified into procedural memory, priming and perceptual learning, classical conditioning, and non-associative learning (Squire, 2004). Figure 2.7 depicts the mammalian long-term memory taxonomy.

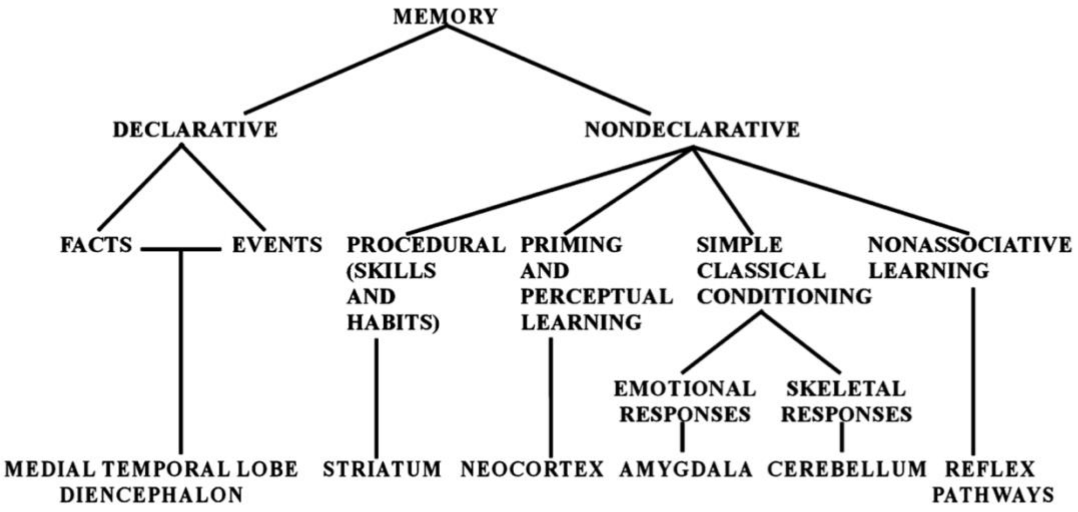


Figure 2.7: Long-term memory taxonomy, from (Squire, 2004)

The hippocampus and its associated structures are critical for the formation of memories and their subsequent reorganization and consolidation into long-term memory. First proposed in 1900 and later confirmed by the writings of Ribot, memory consolidation was classified as the process by which a transient, labile memory is transformed into a more permanent form (Squire et al., 2015). Learned material, when initially encoded, remains sensitive to interference which provides for forgetting. Unless rehearsed, the transient information fails to transform into a permanent state and is therefore lost and must be re-encoded. Structures of the medial temporal lobe play a role in the temporary storage of memory, as damage to the hippocampus and parts of the medial temporal lobe impairs recent memory but spares remote memory in a temporally graded fashion. Structural changes and increased neural activity in the medial temporal lobe after learning highlight the importance of a distribution of cortical networks that represent and express memory as time passes after encoding (Squire, 2004). Once a labile memory is consolidated into long-term memory, it may be retrieved for updating or modulating what was initially encoded, or even disrupted and weakened. Reconsolidation is the process by which a stable long-term memory returns to a labile state, and eventually stabilizes.

The centrality of the hippocampus and medial temporal lobe in forming episodic memory has also been supported by a contextual binding theory. Pertinent to the contextual binding model (Yonelinas et al., 2019) is the role of consolidation. The contextual binding model assumes that episodic memory functions are primarily dependent upon hippocampal activation. Retrieval of episodic information is therefore contextual, composing of the context in which the item to be remembered was initially encoded. From the perspective of the contextual binding model, context includes spatial, temporal, and other sources of information that may be present when information is encoded. The hippocampus is necessary for episodic memory function because it binds together the item to be remembered as well as contextual information that it receives from other brain regions, particularly the neocortex. Tests of free-recall, recognition, and object location therefore rely heavily upon the hippocampus to support familiarity or semantic information. The contextual binding theory also posits that the environmental context changes as the physical and mental state of the individual is altered, which extends the time prior to and after an item-to-be-remembered may be presented. Due to the everchanging role of context, items to be remembered are impacted selectively depending on the temporal period during which they are presented. Context can be beneficial for memory as it enhances the likelihood of remembering temporally similar items in an event (Yonelinas et al., 2019). Physical alteration or physiological arousal induced by exercise prior to or following encoding of items-to-be-remembered could therefore enhance encoding.

The recollection of memories, which involved the recovery of detailed qualitative bits of information incited by some cues is collectively referred to as recall. Functionally different is the process of familiarity which is experienced when a discrimination between a weak intuition to a definitive match is to be made. This process is collectively referred to as recognition, which provides a quantitative measure of whether or not an item was encoded (Eichenbaum et al., 2007). Both memory processes are dissociative and operate in functionally and neuropsychologically distinct manners. However, media temporal lobe activation is apparent during the utilization of either memory process. Evidence for the distinction between familiarity and recollection of events arises from the "what" and "where" pathways (*figure 2.8*). Input to the perirhinal cortex within the medial temporal lobe from association areas that process sensory information provides characteristics about the qualities of items, or the "what" information. Conversely, input to the parahippocampal cortex comes from association areas that process spatial information regarding items, or the "where" information. These streams of processing are distinct, but both converge within the hippocampus. Hippocampal connections are also associated with the entorhinal, perirhinal, and parahippocampal cortices, which provide the underlying bases for recall and recognition memories (Eichenbaum et al., 2007).

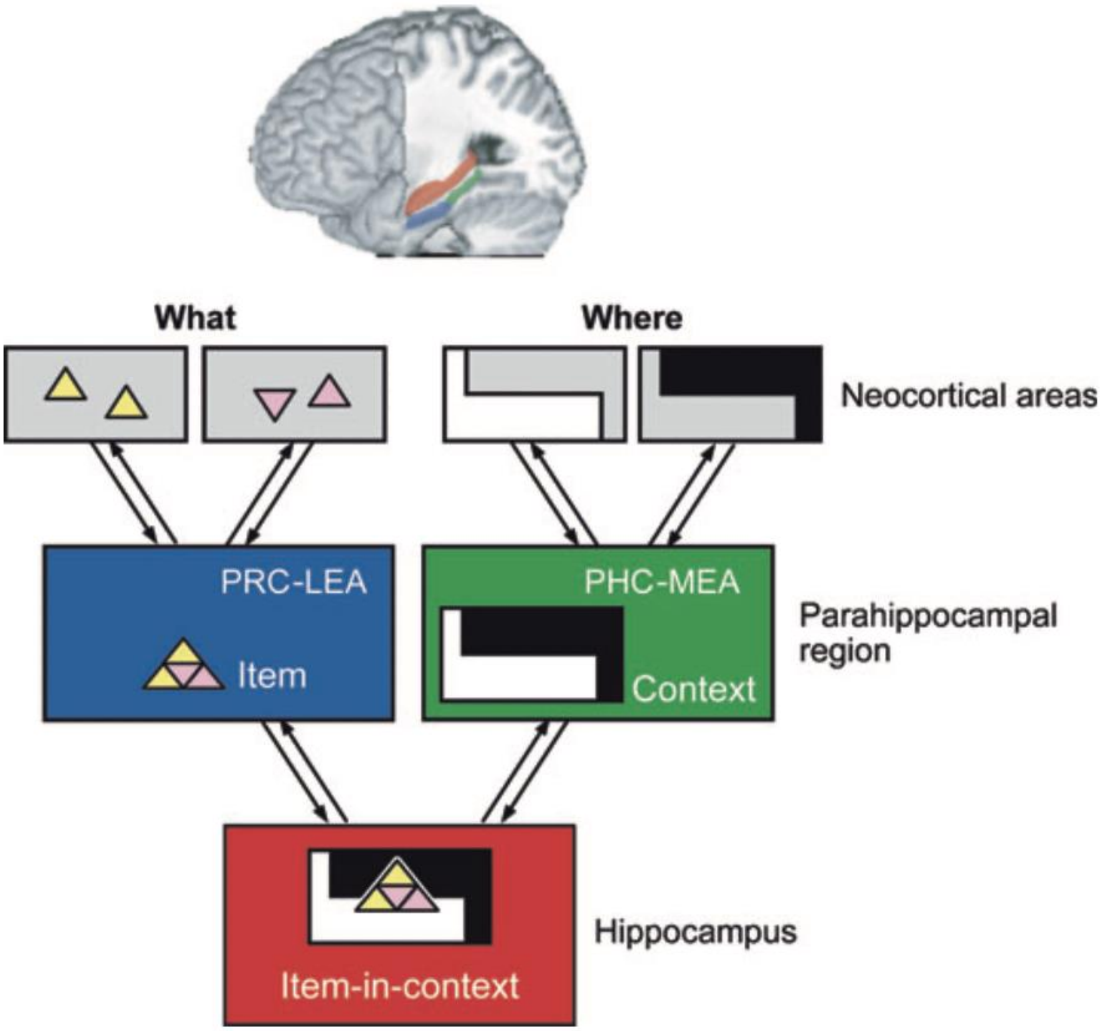


Figure 2.8: The "what" and "where" pathways of the medial temporal lobe, from (Eichenbaum et al., 2007)

2.6 The Relationship Between Attention and Memory

The constructs of attention and memory have intrigued theorists, psychologists, and researchers for centuries. Considerable research has been conducted to answer domains of inquiry regarding both attention and memory. Though many questions remain outstanding, contemporary researchers and scientists have a much deeper understanding of how the psychological constructs of attention and memory operate. Though separable and distinct, attention and memory cannot operate successfully without each other. The construct of attention is often alluded to as the "software of the mind," whereas components of the information processing model that are dictated by memory are conceptualized as the "hardware of the mind." (Tomporowski & Qazi, 2022). Attention determines the amount of information that is successfully encoded, as the division of attention prevents the formation of conscious memory traces. Conversely, past memories influences and guide what stimuli are being attended to. Both higher order executive process, attention and memory have been independently studied for many years. However, the interaction between the two cognitive components has been frequently discussed but infrequently explored. Primary studies that explore memory-related outcomes often fail to acknowledge the role of attentional selection which can modulate encoding under a variety of conditions. Conversely, studies that explore attention often fail to consider the role of perceptual experiences as well past knowledge and how they might influence attentional allocation (Chun & Turk-Browne, 2007).

Attention directly aides the memory encoding process (Chun & Turk-Browne, 2007). However, the details of this modulation remain unclear. The process of 'attending' to a particular task at hand initially involves determining which component of the task will require the allocation of attentional resources while preventing other stimuli from receiving them. Typically, explicit memory tasks demonstrate impaired performances when attentional resources are divided (divided attention) among two separate tasks during encoding (Craik et al., 1996). Explicit episodic memory represents increased activation in the medial and frontal temporal regions during encoding. Investigation of the attention-memory dichotomy is often studied via dual-task paradigms. Dual-tasking consists of the concurrent performance of a motor-motor or a motor-cognitive task that is measured independently (Leland et al., 2017). The simultaneous performance of a primary and secondary task may lead to changes in performance on either or both tasks. Due to a limitation of attentional resources (Kahneman, 1973), there is competition during dual-tasks as to which task consumes more attentional resources. A worsening performance on either task results in dual-task costs, such that there is a decrement in the performance of dual-tasks as opposed to a single-task (Rabaglietti et al., 2019). The cognitive resource theory in part explains individuals' limited ability to perform multiple tasks simultaneously (Vecchio, 1990). This theory posits that the faculties necessary for the attention and information processing consist of a set of limited but renewable resources and the depletion of these resources may occur during demanding tasks (Epling et al., 2016). It is therefore hypothesized that attending to or focusing on a fact or event will enhance the likelihood of successful consolidation. This is implicated in experiments investigating visuospatial memory. When an abundant amount of information is presented to an individual, he/she can selectively attend to and later remember which information is most important (Castel, 2008; Castel et al., 2002; Stefanidi et al., 2018). Selective attention becomes critical to encoding when there is competition between stimuli in the environment. Attention plays a crucial role in forming and maintaining visuospatial associations in memory which are called upon during a visual search when items are to be recalled or recognized. Visuospatial memory is highly dependent upon the "what" and "where" pathways of the medial temporal lobe. Successful visuospatial memory trace matches require the binding of "what" and "where" features of an item; it is insufficient to remember only the visual (the "what" mechanism) or the spatial information (the "where" mechanism) (Siegel & Castel, 2018). How attention modulates implicit memory however it less clear (Chun & Turk-Browne, 2007). Dual-task experiments however present ample evidence that concurrent motor-cognitive activities enhance performance on implicit or automated cognitive tasks (Dietrich & Audiffren, 2011; Etnier et al., 1997).

2.7 The Present Dissertation Research

Given the current evidence, there is a clear relationship between physical activity and attention, as well as physical activity and memory. However, the mechanisms that underlie these relationships as well as the interrelationship between physical activity, memory, and attention have been less frequently explored. Furthermore, there is some evidence to suggest that physical activity complexity impacts how much and how well information is retained across time. However, it is still unclear if the effects of physical activity complexity are universal or selective to different memory processes. The mediating effect of attention between physical activity and long-term memory has not been researched previously. Exploring this relationship empirically will provide contemporary researchers a much deeper understanding of the interlink between how attention may mediate the relationship between physical activity and long-term memory. Given the state of the current evidence that highlights the influence of physical activity on long-term memory and the gaps that are outstanding, the present dissertation was designed in two phases. The first phase of this dissertation includes a systematic review and meta-analysis aimed at summarizing and quantifying the literature regarding acute exercise and long-term episodic memory. The second phase of this dissertation includes a randomized controlled trial aimed at exploring the mechanisms by which acute physical activity influences long-term memory and attention. The aims of the dissertation are as follows:

PHASE 1

Aim 1.1: To identify and quantitatively summarize the existing evidence that explores the relationship between acute bouts of physical activity and long-term episodic memory.

Aim 1.2: To determine the effectiveness of physical activity on long-term memory.

PHASE 2

Aim 2.1: To determine if long-term episodic memory is affected by an acute bout of physical activity that is performed before encoding.

Aim 2.2: To determine if attention mediates the relationship between physical activity and long-term memory.

Aim 2.3: To determine the degree to which physical activity complexity differentially affects memory processes.

Hypothesis 2.1: The primary hypothesis was that young adults who perform a single bout of physical activity immediately prior to encoding will demonstrate more enduring long-term memory performance than young adults who do not exercise prior to encoding.

Hypothesis 2.2: The secondary hypothesis was that attention will significantly mediate long-term memory performance among young adults who perform a bout of physical activity immediately prior to encoding.

Hypothesis 3: The tertiary hypothesis was that mental engagement elicited by complex physical activity will result in superior learning of encoded material compared to control and simple exercise conditions, regardless of the task.

References

Andrade, M., & Walker, N. (2020). *Cognitive Psychology (Andrade and Walker)*. https://socialsci.libretexts.org/Bookshelves/Psychology/Cognitive_Psychology/Cognitive_Psychology_(Andrade_and_Walker)

Atkinson, R. C., & Shiffrin, R. M. (1968). Human memory: A proposed system and its control processes. In *The psychology of learning and motivation: II* (pp. xi, 249–xi, 249). Academic Press. https://doi.org/10.1016/S0079-7421(08)60422-3

Baddeley, A. (2012). Working Memory: Theories, Models, and Controversies. *Annual Review of Psychology*, *63*(1), 1–29. https://doi.org/10.1146/annurev-psych-120710-100422

Broadbent, D. E. (Donald E. (1958). *Perception and communication*.

Castel, A. D. (2008). The adaptive and strategic use of memory by older adults: Evaluative processing and value-directed remembering. In *Skill and strategy in memory use* (pp. 225–270). Elsevier Academic Press.

Castel, A. D., Benjamin, A. S., Craik, F. I. M., & Watkins, M. J. (2002). The effects of aging on selectivity and control in short-term recall. *Memory & Cognition*, *30*(7), 1078–1085. https://doi.org/10.3758/bf03194325

Chang, Y. K., Labban, J. D., Gapin, J. I., & Etnier, J. L. (2012). The effects of acute exercise on cognitive performance: A meta-analysis. *Brain Research*, *1453*, 87–101. https://doi.org/10.1016/j.brainres.2012.02.068

Chun, M. M., & Turk-Browne, N. B. (2007). Interactions between attention and memory. *Current Opinion in Neurobiology*, *17*(2), 177–184. https://doi.org/10.1016/j.conb.2007.03.005

Cooper, S. B., Bandelow, S., Nute, M. L., Dring, K. J., Stannard, R. L., Morris, J. G., & Nevill, M. E. (2016). Sprint-based exercise and cognitive function in adolescents. *Preventive Medicine Reports*, *4*, 155–161. https://doi.org/10.1016/j.pmedr.2016.06.004

Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences*, *24*(1), 87–114. https://doi.org/10.1017/S0140525X01003922

Craik, F. I. M., Govoni, R., Naveh-Benjamin, M., & Anderson, N. D. (1996). The effects of divided attention on encoding and retrieval processes in human memory. *Journal of Experimental Psychology: General*, *125*(2), 159–180. https://doi.org/10.1037/0096-3445.125.2.159

de Greeff, J. W., Bosker, R. J., Oosterlaan, J., Visscher, C., & Hartman, E. (2018). Effects of physical activity on executive functions, attention and academic performance in preadolescent children: A meta-analysis. *Journal of Science and Medicine in Sport*, *21*(5), 501–507. https://doi.org/10.1016/j.jsams.2017.09.595

Dietrich, A., & Audiffren, M. (2011). The reticular-activating hypofrontality (RAH) model of acute exercise. *Neuroscience and Biobehavioral Reviews*, *35*(6), 1305–1325. https://doi.org/10.1016/j.neubiorev.2011.02.001

Eichenbaum, H., Yonelinas, A. P., & Ranganath, C. (2007). The medial temporal lobe and recognition memory. *Annual Review of Neuroscience*, *30*, 123–152. https://doi.org/10.1146/annurev.neuro.30.051606.094328

Epling, S. L., Blakely, M. J., Russell, P. N., & Helton, W. S. (2016). Free recall and outdoor running: Cognitive and physical demand interference. *Experimental Brain Research*, *234*(10), 2979–2987. https://doi.org/10.1007/s00221-016-4700-y

Etnier, J. L., Salazar, W., Landers, D. M., Petruzzello, S. J., Han, M., & Nowell, P. (1997). The influence of physical fitness and exercise upon cognitive functioning: A meta-analysis. In *Database of Abstracts of Reviews of Effects (DARE): Quality-assessed Reviews [Internet]*. Centre for Reviews and Dissemination (UK). https://www.ncbi.nlm.nih.gov/books/NBK67031/

Fan, J., Flombaum, J. I., McCandliss, B. D., Thomas, K. M., & Posner, M. I. (2003). Cognitive and brain consequences of conflict. *NeuroImage*, *18*(1), 42–57. https://doi.org/10.1006/nimg.2002.1319

Fan, J., McCandliss, B. D., Fossella, J., Flombaum, J. I., & Posner, M. I. (2005). The activation of attentional networks. *NeuroImage*, *26*(2), 471–479. https://doi.org/10.1016/j.neuroimage.2005.02.004

Fisher, J. P. (2014). Autonomic control of the heart during exercise in humans: Role of skeletal muscle afferents. *Experimental Physiology*, *99*(2), 300–305. https://doi.org/10.1113/expphysiol.2013.074377

Hergenhahn, B. R. (2008). *An Introduction to the History of Psychology*. Cengage Learning.

Hillman, C. H., Snook, E. M., & Jerome, G. J. (2003). Acute cardiovascular exercise and executive control function. *International Journal of Psychophysiology*, *48*(3), 307–314. https://doi.org/10.1016/S0167-8760(03)00080-1

Hsieh, S.-S., Huang, C.-J., Wu, C.-T., Chang, Y.-K., & Hung, T.-M. (2018). Acute Exercise Facilitates the N450 Inhibition Marker and P3 Attention Marker during Stroop Test in Young and Older Adults. *Journal of Clinical Medicine*, *7*(11), Article 11. https://doi.org/10.3390/jcm7110391

Infantes-Paniagua, Á., Silva, A. F., Ramirez-Campillo, R., Sarmento, H., González-Fernández, F. T., González-Víllora, S., & Clemente, F. M. (2021). Active School Breaks and

Students' Attention: A Systematic Review with Meta-Analysis. *Brain Sciences*, *11*(6), 675. https://doi.org/10.3390/brainsci11060675

Itti, L., Rees, G., & Tsotsos, J. K. (Eds.). (2005). *Neurobiology of Attention* (1st edition). Academic Press.

Janssen, M., Toussaint, H. M., van Mechelen, W., & Verhagen, E. A. (2014). Effects of acute bouts of physical activity on children's attention: A systematic review of the literature. *SpringerPlus*, *3*, 410. https://doi.org/10.1186/2193-1801-3-410

Jonides, J., Lewis, R. L., Nee, D. E., Lustig, C. A., Berman, M. G., & Moore, K. S. (2008). The mind and brain of short-term memory. *Annual Review of Psychology*, *59*, 193–224. https://doi.org/10.1146/annurev.psych.59.103006.093615

Kahneman, D. (1973). *Attention and Effort*. Prentice-Hall.

Langille, J. J., & Brown, R. E. (2018). The Synaptic Theory of Memory: A Historical Survey and Reconciliation of Recent Opposition. *Frontiers in Systems Neuroscience*, *12*, 52. https://doi.org/10.3389/fnsys.2018.00052

Leland, A., Tavakol, K., Scholten, J., Mathis, D., Maron, D., & Bakhshi, S. (2017). The Role of Dual Tasking in the Assessment of Gait, Cognition and Community Reintegration of Veterans with Mild Traumatic Brain Injury. *Materia Socio-Medica*, *29*(4), 251–256. https://doi.org/10.5455/msm.2017.29.251-256

Lindsay, G. W. (2020). Attention in Psychology, Neuroscience, and Machine Learning. *Frontiers in Computational Neuroscience*, *14*. https://www.frontiersin.org/articles/10.3389/fncom.2020.00029

Mahar, M. T. (2011). Impact of short bouts of physical activity on attention-to-task in elementary school children. *Preventive Medicine*, *52 Suppl 1*, S60-64. https://doi.org/10.1016/j.ypmed.2011.01.026

Malmberg, K. J., Raaijmakers, J. G. W., & Shiffrin, R. M. (2019). 50 years of research sparked by Atkinson and Shiffrin (1968). *Memory & Cognition*, *47*(4), 561–574. https://doi.org/10.3758/s13421-019-00896-7

McMorris, T. (2016). Developing the catecholamines hypothesis for the acute exercise-cognition interaction in humans: Lessons from animal studies. *Physiology & Behavior*, *165*, 291–299. https://doi.org/10.1016/j.physbeh.2016.08.011

McMorris, T. (2021). The acute exercise-cognition interaction: From the catecholamines hypothesis to an interoception model. *International Journal of Psychophysiology*, *170*, 75–88. https://doi.org/10.1016/j.ijpsycho.2021.10.005

McMorris, T., Hale, B. J., Corbett, J., Robertson, K., & Hodgson, C. I. (2015). Does acute exercise affect the performance of whole-body, psychomotor skills in an inverted-U fashion? A meta-analytic investigation. *Physiology & Behavior*, *141*, 180–189. https://doi.org/10.1016/j.physbeh.2015.01.010

Nobrega, A. C. L., O'Leary, D., Silva, B. M., Marongiu, E., Piepoli, M. F., & Crisafulli, A. (2014). Neural Regulation of Cardiovascular Response to Exercise: Role of Central Command and Peripheral Afferents. *BioMed Research International*, *2014*, e478965. https://doi.org/10.1155/2014/478965

Marrocco, R. T., & Davidson, M. C. (1998). Neurochemistry of attention. In *The attentive brain* (pp. 35–50). The MIT Press.

Northey, J. M., Cherbuin, N., Pumpa, K. L., Smee, D. J., & Rattray, B. (2018). Exercise interventions for cognitive function in adults older than 50: A systematic review with meta-analysis. *British Journal of Sports Medicine*, *52*(3), 154–160. https://doi.org/10.1136/bjsports-2016-096587

Posner, M. I., & Rothbart, M. K. (2007). Research on attention networks as a model for the integration of psychological science. *Annual Review of Psychology*, *58*, 1–23. https://doi.org/10.1146/annurev.psych.58.110405.085516

Rabaglietti, E., De Lorenzo, A., & Brustio, P. R. (2019). The Role of Working Memory on Dual-Task Cost During Walking Performance in Childhood. *Frontiers in Psychology*, *10*, 1754. https://doi.org/10.3389/fpsyg.2019.01754

Ranganath, C., & Blumenfeld, R. S. (2005). Doubts about double dissociations between short- and long-term memory. *Trends in Cognitive Sciences*, *9*(8), 374–380. https://doi.org/10.1016/j.tics.2005.06.009

Rose, N. S., Myerson, J., Roediger, H. L., & Hale, S. (2010). Similarities and differences between working memory and long-term memory: Evidence from the levels-of-processing span task. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *36*(2), 471–483. https://doi.org/10.1037/a0018405

Samuel, R. D., Zavdy, O., Levav, M., Reuveny, R., Katz, U., & Dubnov-Raz, G. (2017). The Effects of Maximal Intensity Exercise on Cognitive Performance in Children. *Journal of Human Kinetics*, *57*, 85–96. https://doi.org/10.1515/hukin-2017-0050

Schmidt, R. A., & Lee, T. D. (2011). *Motor control and learning: A behavioral emphasis, 5th ed* (pp. ix, 581). Human Kinetics.

Schmidt, R. A., Lee, T. D., Winstein, C., Wulf, G., & Zelaznik, H. N. (2018). *Motor Control and Learning: A Behavioral Emphasis* (Sixth edition). Human Kinetics.

Siegel, A. L. M., & Castel, A. D. (2018). The Role of Attention in Remembering Important Item-Location Associations. *Memory & Cognition*, *46*(8), 1248–1262. https://doi.org/10.3758/s13421-018-0834-4

Squire, L. R. (2004). Memory systems of the brain: A brief history and current perspective. *Neurobiology of Learning and Memory*, *82*(3), 171–177. https://doi.org/10.1016/j.nlm.2004.06.005

Squire, L. R., & Wixted, J. T. (2011). The Cognitive Neuroscience of Human Memory Since H.M. *Annual Review of Neuroscience*, *34*, 259–288. https://doi.org/10.1146/annurev-neuro-061010-113720

Squire, L. R., Genzel, L., Wixted, J. T., & Morris, R. G. (2015). Memory consolidation. *Cold Spring Harbor Perspectives in Biology*, *7*(8), a021766. https://doi.org/10.1101/cshperspect.a021766

Stefanidi, A., Ellis, D. M., & Brewer, G. A. (2018). Free recall dynamics in value-directed remembering. *Journal of Memory and Language*, *100*, 18–31. https://doi.org/10.1016/j.jml.2017.11.004

Tomporowski, P. D., & Qazi, A. S. (2022). *Motor Skill Behavior* [Text]. Great River Learning. https://www.greatriverlearning.com/product-details/2053

Tomporowski, P. D., McCullick, B., Pendleton, D. M., & Pesce, C. (2015). Exercise and children's cognition: The role of exercise characteristics and a place for metacognition. *Journal of Sport and Health Science*, *4*(1), 47–55. https://doi.org/10.1016/j.jshs.2014.09.003

Vecchio, R. P. (1990). Theoretical and empirical examination of cognitive resource theory. *Journal of Applied Psychology*, *75*(2), 141–147. https://doi.org/10.1037/0021-9010.75.2.141

Yonelinas, A. P., Ranganath, C., Ekstrom, A. D., & Wiltgen, B. J. (2019). A contextual binding theory of episodic memory: Systems consolidation reconsidered. *Nature Reviews. Neuroscience*, *20*(6), 364–375. https://doi.org/10.1038/s41583-019-0150-4

CHAPTER 3

THE EFFECTS OF ACUTE EXERCISE ON LONG-TERM EPISODIC MEMORY: A SYSTEMATIC REVIEW AND META-ANALYSIS[1]

---

[1] Accepted by *Frontiers in Cognition*. Reprinted here with permission of publisher, November 18th, 2024.

Abstract

Research findings reveal a relationship between acute bouts of exercise and procedural/declarative memory. Prior systematic reviews report small/moderate effects of acute exercise on episodic long-term declarative memory. A somewhat overlooked issue is the influence of exercise on specific types of episodic memory processing. The primary focus of this systematic review and meta-analysis was to evaluate the effects of acute bouts of exercise prior to, during, and following encoding on free-, cued-recall, and recognition episodic memory. PubMed, Scopus, and EBSCO databases were entered, and 42 experiments were subject to meta-analysis. Exercise prior to encoding improved memory (d = 0.23) and affected free-recall (d = 0.40) tests of memory more than cued-recall (d = 0.08) or recognition (d = −0.06) memory. Exercise following encoding improved memory (d = 0.33) and affected recognition (d = 0.62) memory more than free- (d = 0.19) or cued-recall (d = 0.14) memory. Exercise during encoding did not influence memory (d = −0.04). Moderator analyses revealed that exercise before encoding impacted memory differentially on the basis of age, exercise type, and test-timing. When exercise occurred after encoding, age and exercise type, but not timing of the test influenced memory performance. Exercise before and after encoding has selective effects on episodic memory. Additional experiments that evaluate how bouts of exercise influence memory encoding are warranted.

Keywords**:** episodic memory, memory encoding, long-term memory, acute exercise, free-recall, recognition, cued-recall

3.2 Introduction

There has been a marked increase in recent years in studies of the effects of individual bouts of exercise on long-term memory. Much of this research activity was spurred by several literature reviews that provide clear support for the view that acute exercise enhances memory (Lambourne & Tomporowski, 2010; Roig et al., 2013). Reviewers conclude that the strength of the acute exercise-memory relation is moderated by such characteristics as the type of exercise performed and its intensity and duration, the temporal relation between exercise and encoding, and the delay between encoding and testing. Questions remain, however, concerning the degree to which the impact of exercise depends on the manner in which memories are processed, stored, and retrieved. Answers to these questions have implications for both researchers and practitioners who are interested in designing exercise or broader physical activity interventions that can maximally affect memory and learning.

A meta-analytic review of the exercise-memory literature conducted by Roig et al. (2013) categorized memory tasks in terms of short-term and long-term memory tests. Studies were classified on the basis of the time between encoding and testing, with delays longer than 2 min categorized as long-term memory. Further, long-term memory tests were divided into declarative (episodic or semantic) and non-declarative (procedural) memory tests. The results of seven experiments indicated that acute bouts of exercise enhanced performance on long-term procedural and declarative memory tests, with moderate to large effect sizes. More recently, Loprinzi et al. (2019a) focused specifically on the effects of acute bouts of exercise on short-term and long-term episodic memory. The authors' review of 25 experiments provided information concerning the temporal relation between exercise bouts and encoding (prior, during, and following encoding) and such study characteristics as exercise type, intensity, and duration.

Exercise performed prior to and following encoding enhanced performance, with larger effect sizes when exercise was performed following encoding than prior to encoding. Exercise performed during encoding had a negative effect on episodic memory.

The meta-analytic reviews by Roig et al. (2013) and Loprinzi et al. (2019a) and others (Lambourne and Tomporowski, 2010) support a causal relation between acute exercise and memory storage. These reviews also clarify exercise parameters and individual difference factors that influence the strength of the relation. Yet to be addressed, however, are questions concerning the uniformity of acute exercise effects across different forms of memory. The memory tests employed in experiments evaluated in previous reviews vary widely and the cognitive processes involved in performing individual tests cannot be clearly delineated. Roig et al. (2013), for example, included tests of verbal fluency, associative memory, paragraph reading, code-substitution, object recognition tasks, and an assortment of word recall tests. Similarly, Loprinzi et al. (2019a) included studies that employed the California Verbal Learning Test, Rey Auditory Verbal Learning Test (RAVLT), paragraph recall, image recognition, recall of filmed scenarios, and laboratory constructed tests. The consensus among re-searchers is that humans possess several different types of memory, all of which are maintained via underlying brain networks (Schacter et al., 1999; Squire and Wixted, 2011; Eichenbaum, 2017; Loprinzi et al., 2017) and are controlled by cognitive processes that are involved in encoding and retrieval (Wilson and Criss, 2017).

The present systematic review was designed to provide clarity concerning the effects of exercise on long-term memory by focusing on episodic memory, a type of declarative memory that is involved in storing information about temporally arranged or dated events. Acute exercise experiments typically involve asking participants to study material (e.g., words) in conjunction with a bout of exercise. Episodic memory is typically measured via tests of recognition, cued-recall, or free-recall. Recognition tests are characterized by methods in which a participant is asked to identify whether or not a specific item (e.g., word) was previously presented. Cued-recall tests often involve the presentation of pairs of items (e.g., word pairs), one of which is to be remembered while the other serves as a priming stimulus that assists in the reintegration of the targeted item. Free-recall tests require an individual to remember target items without the aid of cues. Recognition memory test performance is typically considered easier than cued- and free-recall test performance because the participant is not required to generate a memory of the item and then determine if it was previously seen (Malmberg et al., 2019).

Numerous psychological theories of memory have been proposed to explain how sensory experiences are manipulated and stored in memory and how stored memories are retrieved (Malmberg et al., 2019). An important contribution to memory research was a model of memory processing introduced by Atkinson and Shiffrin (1968, 1971). Central to their theory was conceptualization of the processes of a short-term memory buffer and its relation to long-term storage and retrieval. Theory- based experimentation over the course of five decades led to several modifications and an eventual reconceptualization of the processes involved in recall and recognition memory. The Search of Associative Memory (SAM) (*figure 3.1*) (Raaijmakers and Shiffrin, 1981; Gillund and Shiffrin, 1984) and Retrieving Effectively from Memory (REM) (*figure 3.2*) (Cox and Shiffrin, 2017) models emerged; they continue to guide contemporary memory research (Malmberg et al., 2019). As shown in Figure 3.1, the SAM model of episodic memory is based on the assumption that experienced events are held in short-term memory where rehearsal processes create separate memory traces that strengthen as new information is added. Retrieval consists of a search process in which multiple traces are sampled; selection is based on trace strength. Long- term forgetting is thought to be due to interference and search termination rather than a function of a decay in trace strength. Central to the SAM model is the prediction that memory retrieval reflects a dual-coding process that includes memories of the items to be re-membered and memories of the environmental context present when items are studied. During encoding, the environmental setting provides “background” information (e.g., location, mood, temperature, arousal) that is not experimentally varied and is not the focus of the experiment. Recall and recognition memory performance reflects the combination of the strength of individual memory traces for items and for context. As shown in Figure 3.2, the SAM-REM model makes explicit assumptions concerning strengths of item and context memory and how trial- to-trial variations (e.g., list length, item similarity) create “noise” that affects memory retrieval (Criss and Shiffrin, 2004). The environmental context in which items are encoded contribute to how well memory search leads to an appropriate match. Retrieval from long-term memory involves sampling of memory traces and a reconstructive process that involves probabilistic judgements based on the relevance of sample traces (Criss and Shiffrin, 2004).

The SAM-REM models describe different processes for free- recall and recognition. For free recall, there is a competition among memory traces; selection is based on how well an internally generated context cue matches the context stored in a trace. Episodic recognition memory does not require the generation of past episodic details from memory. All that is required is to distinguish an item that is presented during the context of encoding from foils that were not presented. Free recall is often described synonymously as remembrance, whereas recognition reflects familiarity. Confusion during recognition memory is created by noise associated with items experienced in different environmental contexts.

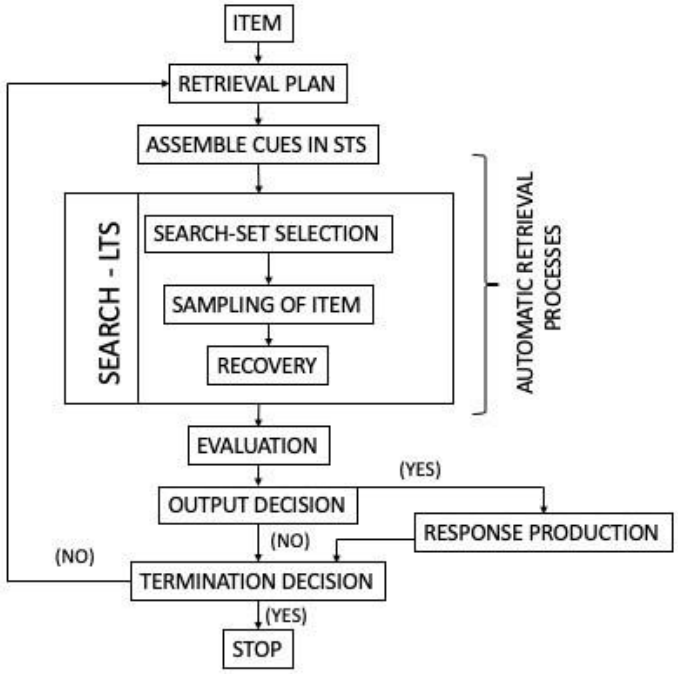


Figure 3.1. A generalized depiction of the various phase of retrieval (STS = short-term search; LTS= long-term search) (Modified from Raaijmaker, J. G. W., & Shiffrin, R. M. (1981). Search of associative memory. Psychological Review, 88, p.97)

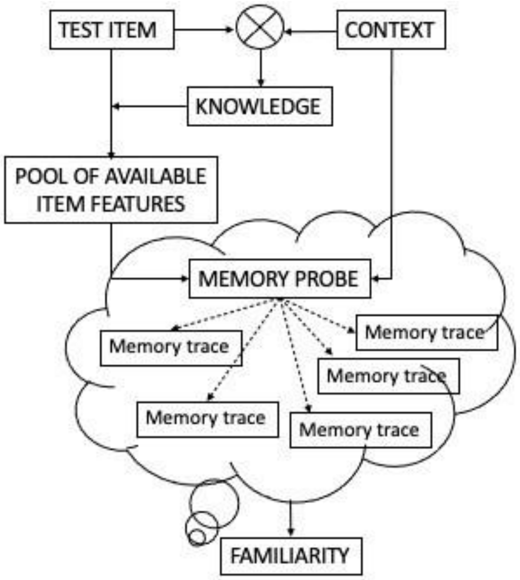


Figure 3.2. Schematic depiction of the recognition process. A memory probe is formed from a combination of the current context and both physical and semantic features of the test item. Item features are gradually sampled into the probe which is continually compared in parallel to all the

> traces in memory, each of which is activated to a degree depending on the similarity between features in the probe and those in the trace. To make a recognition decision, a participant tracks changes in the overall level of activation of these traces – termed “familiarity – from an initial level determined by context alone.” (Modified from Cox, G. E., & Shiffrin, R. M. (2017). A dynamic approach to recognition memory. Psychological Review, 124, p. 797)

Acute bouts of exercise are hypothesized to produce systemic changes in physiological arousal and alterations in neural noise that affect neural networks involved in executive processing and mental performance (McMorris, 2016a) and memory storage (McGaugh, 2015; Meeusen et al., 2017). Several narrative and systematic reviews conclude that acute bouts of exercise affect working-term memory processes and decision-making speed (Tomporowski, 2003; Lambourne and Tomporowski, 2010; Chang et al., 2012; McMorris and Hale, 2015). The physiological changes that occur during a bout of exercise may also influence the strength of item and context memory traces stored in memory, which would facilitate memory retrieval. Several neurophysiological mechanisms have been identified that may explain how acute exercise improves memory processes. Functional changes in neurotransmission, neurotrophic factors (e.g., BDNF and vascular endothelial growth factor), increased blood flow, receptor activity, and glucose/oxygen metabolism may ensue as a result of acute bouts of exercise (Loprinzi et al., 2017; El-Sayes et al., 2019; Loprinzi, 2019). Increases in neurotrophic and growth factors have been shown to improve cellular processes that lead to structural changes that are correlated with behavioral change. Neurophysiological adaptations may improve the encoding, storage, and retrieval of memory items. Given the evidence for the existence of different types of memory stores, which differ in their underlying mechanisms, it is of theoretical and practical interest to determine whether acute exercise has a global effect on all types of memory processing, or whether the effects are selective.

The standard view of salutary interventions, such as physical activity and exercise, is that they promote global brain health, which leads to gains in cognition (Hillman et al., 2008). Theory-based research conducted over the past decade on the neurobiology of memory provides evidence to suggest that environmental and contextual factors exert selective effects on episodic memory. Reviews of experiments that examine both behavioral and neurophysiological outcomes reveal that contextual manipulations differentially influenced free-recall and recognition memory (Eichenbaum et al., 2007; Yonelinas et al., 2019). The pattern of results obtained under contextual conditions present during encoding (e.g., study time, elaboration, attention, and rote repetition) and retrieval (e.g., attention and test delay), are explained in terms of specific neurological structures and networks. Tests that involve the recollection of items are dependent on hippocampal structures while tests of familiarity and recognition depend on parahippocampal structures and the entorhinal cortex (Brickman et al., 2014). The double anatomical dissociation observed in clinical studies conducted with individuals with amnesia and laboratory experiments conducted with humans, monkey, and rats indicate that contextual factors may differentially impact underlying neural networks that are involved in episodic memory (Yonelinas et al., 2019). Such studies provide clear evidence that there exists a distinct double dissociation among several brain structures responsible for the consolidation of long-term memory. This double dissociation between the perirhinal cortex and hippocampus has been implicated among animal models to produce differential outcomes with respect to recognition, spatial, and recall memory (Winters et al., 2004). Given that acute bouts of physical activity impact episodic memory similarly to other contextual contexts, it will shed light on the neuroanatomical pathways that impact memory storage and retrieval as well as help predict the effectiveness of specific educational methods designed to benefit long-term memory.

The present review extends previous literature analyses (Roig et al., 2013; Loprinzi et al., 2019a) by focusing on the effects of acute bouts of exercise performed before, during, and after encoding on specific types of episodic memory processes described in contemporary psychological theory and neurobehavioral hypotheses.

3.3 Materials & Methods

The primary aim of the present paper was to conduct a systematic review and meta-analysis to assess the impact of acute bouts of exercise on episodic memory. The systematic review protocol was registered with International Prospective Register of Systematic Reviews on 27th August 2020 (CRD42020202784) and adheres to the Preferred Reporting Items for Systematic Review and Meta-Analysis Protocols (PRISMA-P). We undertook a two-stage search process to identify relevant articles for the meta-analysis; first, a search of scientific databases, and then a manual search of the reference lists of included studies for additional papers not previously identified. We also conducted a follow-up search procedure in February 2023 to identify any additional references that were subject to our systematic review. The secondary search methods were identical to the primary search. These methods for systematic review and meta-analysis were in line with those used previously (Siddaway et al., 2019).

Three commercial platforms (Pubmed, Scopus and EBSCO) hosting six scientific databases (CINAHL Complete, ERIC, MEDLINE, APA PsycArticles, APA PsycInfo, SPORTDiscus with Full Text) were searched in March 2020 and then once again in November 2020. Databases were searched in English. The PRISMA flow diagram illustrating retrieval is presented in figure 3.3. Following searches, reference lists of identified articles and previous systematic reviews were reviewed to identify further relevant studies. As shown in figure 3.3, the database search identified 6,855 references. In 1,708 duplicates were identified and removed, leaving 5,147 references for screening. The first screening phase (titles and abstracts) yielded 90 references for full text screening after 5,057 references were excluded. Of these, 48 were excluded, leaving 42 to meet our inclusion criteria. The review considered studies published in English; no date limits were set. Both control trials and cross-over trials were included. Studies were excluded when they did not meet the key inclusion criteria described below. Gray literature was not consulted, on the basis that most rigorous studies will include peer-reviewed consideration. The secondary search resulted in 967 references. Seven hundred and sixty five duplicates were identified and removed, leaving 202 for full text screening. The initial screening phase (title and abstract) yielded 11 references for full text review. Following the full text review, 6 references met our inclusion criteria and were included in the secondary analysis.

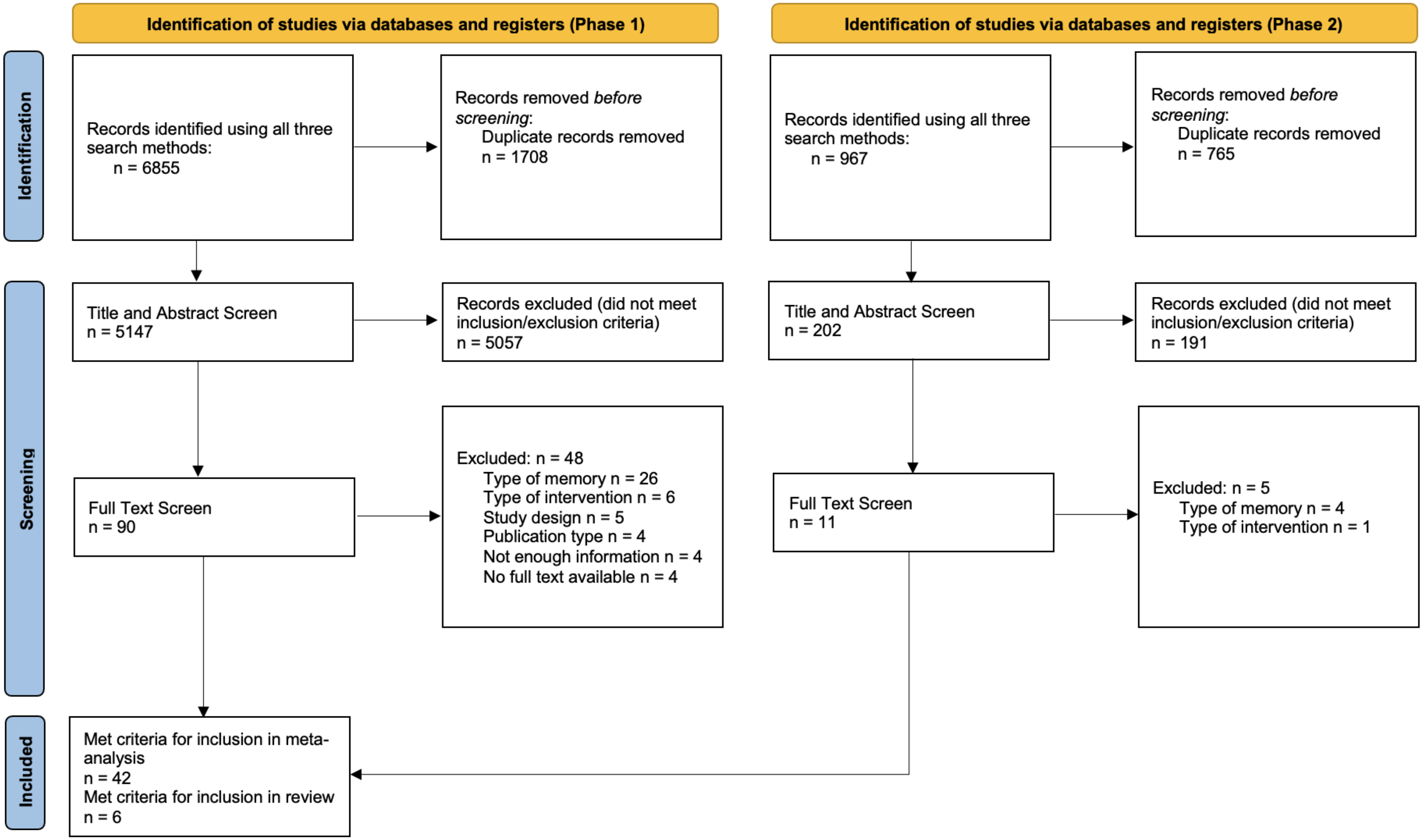


Figure 3.3. PRISMA diagram depicting flow of studies

3.3.1 Inclusion/exclusion criteria

The keyword search strategy was iteratively developed via the author team. Key search terms and their derivatives were pooled in two key themes related to memory and the mode of exercise prior to being combined for the final searches. The population specified human participants aged 5 years or older. The environment was not specified to enable a broad array of studies in both lab and field-based settings. The intervention type was an acute bout of exercise before, during, or after an encoding task, that may be a repeated design within a day or in a cross-over condition. The exercise modes were developed through an initial review of the literature to identify all of the acute exercise modes. The outcome measures were aligned to memory types (long-term declarative memory, semantic memory, episodic memory, and spatial memory) and memory assessment (free- recall, cued-recall, recognition, paired-associate, object location, sentence recall, and word fluency). Exclusion criteria was opposite to the inclusion criteria, in addition to the studies included; participants who reported suffering from a concussion or similar head trauma within the past 6 months, studies on participants prescribed psychotropic medications, a condition that influences memory (e.g., learning disorders, developmental disorders, specific clinical diagnosis based on memory disorders), studies focused on specific health conditions (e.g. cancer, diabetes), no assessment of memory retention over time, and studies that used the following designs: cross-sectional studies, longitudinal studies, or chronic studies (more than one bout of exercise over an extended period of time or extending two or more days).

3.3.2 Article Screening and Data Extraction

All articles retrieved as part of the scientific platform search were downloaded into an Endnote database and duplicates were removed. One author (NG) performed a title and abstract screen while a second author (AD-S) performed a random check of 20% of the articles. Before performing a full-text screen, the inclusion/exclusion criteria outlined above was applied. All authors performed full text screening of articles that met the initial criteria. Once the final eligible studies were identified, a second search of the literature was conducted by assessing the accompanying reference sections. The reference sections were manually searched, cited articles were extracted by hand, and the article name, authors and date of publication were inserted into an Excel spreadsheet. These extractions were cross checked against the original Endnote database, duplicates were identified and removed, and all titles and abstracts were assessed prior to proceeding to a full-text screen by all authors using Google Scholar. Several discrepancies in the application of selection criteria were identified within the selection process but were resolved through consensus with all co-authors. Study characteristics, effect size data, and data for moderator variable coding were extracted from all eligible articles. At the onset of coding, approximately 10% of articles were double–coded and any inconsistencies were discussed. Upon consensus between all authors, the remaining articles were single-coded by KL and cross-checked for accuracy (PT and AQ). Data extracted to an Excel spreadsheet included author names, publication year, study design, sample type and characteristics (gender, age, sample size), memory test characteristics (timing, type), exercise protocol (type, mode, intensity, length), and results.

The screening and data extraction process for the secondary search was identical to the primary search. Two authors (AQ and DS) performed a title and abstract screening. Similar to the primary search, study characteristics and effect size data were extracted from all articles. All data was cross checked for accuracy (AQ and DS) and any discrepancies were resolved through consensus.

3.3.3 Assessment of Study Quality

Consistent with PRISMA-P guidelines, two independent reviewers (NG and AD-S) assessed overall and subdomain risk of bias using a modified version of the Downs and Black (Downs and Black, 1998) checklist for methodological quality for both randomized and non-randomized studies of health care interventions (Daly-Smith et al., 2018). The use of the modified criteria reflected the need for a risk-of-bias tool that was specific to acute experimental studies. Study authors further developed the criteria to address specific issues discussed in previous reviews. Standardization was used on three papers. The remaining papers were divided equally between the two authors for assessment. A 20% sample of both authors' assessment was moderated by the other reviewer. Disagreements between re- view authors over the risk of bias were resolved by discussion, with a review of the specific criteria being performed on all non-moderated papers.

Assessment of study quality for the secondary search was identical to the primary search and was conducted independently by two authors (AQ and DS). Any disagreements between the authors were resolved via discussion.

3.3.4 Meta Analytic Methods

To assess the effect of acute exercise on different encoding paradigms (encoding before exercise, during exercise, or following exercise), three separate meta-analyses were conducted. Meta- analyses were conducted using Comprehensive Meta-Analysis CMA software (Version 3 for Windows, Biostat company, Englewood NJ, USA). CMA enables the harmonization of data presented in different formats and from different study designs (i.e., between-subjects, within-subjects). Cohen's d was calculated when means, standard deviations, and sample sizes were available. When these data were not available, Cohen's d was estimated using t or p values and sample size information. Cohen’s d was used to control for Type I error rates (Huedo-Medina et al., 2006). Effect sizes were calculated such that a beneficial effect of acute exercise on long-term memory was indicated by a positive effect size. The degree of heterogeneity of the effect sizes was evaluated with the Cochran’s Q-statistic. Egger’s regression test was used to evaluate the potential publication bias.

Categorical moderators were determined a priori and were chosen based on logical, theoretical, and previous empirical relations between acute exercise and episodic memory. Similar to the previous meta-analysis by Loprinzi et al. (2019a), cardiorespiratory fitness was not examined because few studies reported the measure. The acute exercise paradigm was coded as exercise prior to encoding, exercise during encoding, and exercise following encoding. Episodic memory type was coded as free-recall, cued-recall, and recognition. The timing of the memory test was coded as same day, 1 day later, 2 days later, 1 week later, and 2 weeks later. Age was categorized as elementary (6–13 years), high school (14–17 years), young-adult (18–24 years), adult (25–44 years), middle-age (45–60 years), and older adults (>60 years) (Roig et al., 2013; Loprinzi et al., 2019a). Sex was coded as males, females, mixed, predominately male (>70% of sample), or predominantly female (>70% of sample). For the exercise protocol, exercise was coded by type (aerobic, anaerobic, or muscular resistance), mode [running/walking, cycling, other (e.g., circuit training, resistance training, stepping)], duration (very short = 10 min or less, short = 11–20 min, medium = 21–39 min, long ≥ 40 min), and intensity (low, low to moderate, moderate, high) (Garber et al., 2011; Roig et al., 2013). Note that many different metrics for exercise intensity were used (RPE, HRR, max HR, etc.) which made it difficult to apply standard thresholds such as those suggested by the American College of Sports Medicine. The author’s descriptor of the intensity level was used when provided; when it was not stated we used our expert judgement. Moderators also included study quality (excellent, good, fair, or poor) (O’Connor et al., 2015) and study design (between-subjects, within-subjects).

Moderators were tested using Q with a mixed effects analysis. Heterogeneity was determined by Cochrane’s Q statistic and I^2 values, whereby values of <25, 50, and 75 were considered to indicate low, moderate, and high levels of heterogeneity, respectively (Higgins et al., 2003). Subgroup moderator analyses were conducted for the encoding paradigms if I^2 values demonstrated at least moderate heterogeneity.

3.4 Results

3.4.1 Articles Included in Analyses

Using the predefined search strategies, three stages of article searches were conducted. At the conclusion of the first stage, 23 articles were considered eligible for inclusion in the final meta- analysis. At the conclusion of the second stage, 12 articles were deemed eligible for inclusion in the final meta-analysis. At the conclusion of the third stage, 7 articles were considered eligible for inclusion in the final meta-analysis.

In total, 42 articles met the inclusionary criteria and were used for quantitative analyses in the present meta-analytic review. Table 3.1 provides a summary of the included experiments

Author(s), Year, & Country	Participant Characteristics			Exercise Intervention					Study Design	Type of memory assessed	Memory assessment	Time between encoding and recall/recognition
	N	Age	Sex	Duration	Intensity	Mode	Control	Temporal Period				
Amico & Schaefer, 2020 (US) [29]	78	31.03 (3.6)	39 F 39 M	-	Mod	Running, Dribbling	Standing	During	Between	Cued recall (words)	Vocabulary learning task	Immediate 24 hours
Austin & Loprinzi, 2019 (US) [30]	20	21.6 (0.7)	50% F 50% M	10 mins	-	Treadmill	Sudoku	Before	3-arm Within subjects	Free recall (words)	RAVLT	10 mins
Coles & Tomporowski, 2008 (US) [31]	18	22.2 (1.6)	NK	40 mins	Mod	Cycle ergometer	Rest watching documentary	Before	Within subjects	Free recall (words)	Visual free recall test	100 seconds 12 mins
Frith, Sng, & Loprinzi, 2017 (US) [32]	88	21.9 (2.4)	45.5% M 54.5% F	15 mins	High	Treadmill	Sitting	Before During After	Between subjects	Free recall (words)	RAVLT	20 mins 24 hours
Haynes & Loprinzi., 2019 (US) [33]	24	20.9 (1.9)	66.7 F	15 mins	Mod	Treadmill	Rest for 5 mins	Before During After	Within subjects	Free recall and recognition (words)	RAVLT	20 mins 24 hours
Delancey et al., 2019 (US) [34]	40	Exp – 21.9 (0.6) Cont – 20.8 (0.3)	~50% F ~50% M	15 mins	Low Mod High	Treadmill	No exercise	After	Between subjects	Free recall (words)	RAVLT	24 hours
Dilley, Zou, & Loprinzi, 2019 (US) [35]	60	20.8	Cont – 80% F Mod – 95% F High – 95% F	15 mins	Mod High	Treadmill	Sudoku	Before	Between subjects	Cued-recall and Recognition (words)	DRM Paradigm	Immediate 10 mins

Etnier et al., 2014 (US) [36]	43	11-12	28 F 15 M	To exhaustion	High	PACER Test	No treatment control	Before	Between subjects	Free recall and recognition (words)	RAVLT	2 mins 24 hours
Hotting et al., 2016 (Germany) [37]	81	22 (2.36)	41 M 40 F	To exhaustion	Low High	Cycle ergometer	Relaxing	After	Between subjects	Cued recall (words)	Polish-German Vocab test	20 mins 24 hours
Johnson et al., 2019 (US) [38]	24	21.5 (1.2)	54.2% F 45.8% M	10 mins	Mod	Sprints on indoor court	No control	Before	Within subjects	Cued recall (words)	Paired associative learning task	10 mins
Jentsch & Wolf, 2020 (Germany) [39]	48	23.38(2.86)	26 F 22 M	20 mins	High	Treadmill	Seated rest watching documentaries	After	Between subjects	Recognition (pictures)	Visuospatial IAPS memory task	24 hours
Kao et al., 2018 (US) [40]	36	21.5	18 F 18 M	16 mins	High Moderate	Treadmill	Rest	Before	Within subjects	Free recall (words)	Visual free recall task	Immediate 13 mins
Labban & Etnier, 2011 (US)[41]	48	22.02	33 F 15 M	20 mins	Moderate	Cycle ergometer	Rest	Before After	Between subjects	Free recall (story)	Guild Memory Test	35 mins
Labban & Etnier, 2018 (US) [42]	15	22.73	10 F 5 M	30 mins	Moderate	Cycle ergometer	Rest	Before After	Within subjects	Free recall and recognition (words)	RAVLT	60 mins 24 hours
Lind et al., 2019 (Denmark) [43]	81	11.8	33 F 48 M	20 mins	Mod/High Low	Football Football (walking)	Rest	After	RCT	Recognition (pictures)	Visual Memory Task	7 days
Loprinzi, Crawford et al., 2020 (US) [44]	23	20.4(1.3)	65.2% F	15 mins	Moderate	Treadmill	Rest	Before	Within subjects	Free recall (words)	Word list	20 mins
	28	23.1(5.2)	46.4 % F	0 mins								
	31	21.5(2.8)	58.1% F	0 mins								

	20	21.5(1.5)	50% F 50% M	15 mins								
	28	23.1(5.2)	46.4% F	0 mins								
	73	21(1.7)	72% F	0 mins								
Loprinzi, Green et al., 2020 (US) [45]	40	21	47.5% F 52.5% M	15	Moderate	Circuit – body weight (resistance)	Sudoku	Before	Between subjects (2 arm parallel RCT)	Free recall (words, item location)	RAVLT Treasure Hunt Task	Immediate 10 mins
	51	21.7	68.3% F 31.7% M						Between subjects (3 arm parallel RCT)			
Loprinzi, Harris et al., 2019 (US) [46]	80	20.9 (1.2)	61.3% F, 38.7% M	15 mins	Low	Treadmill	Rest with Sudoku	Before	Between subjects	Free recall (story)	Logical memory task	Immediate 20 mins
	77	21.10 (3.3)	50% F, 50% M	0 mins	High					Free recall (story)	Logical memory task	
	80	21.04 (1.5)	65% F, 35% M	15 mins	High					Free recall (words)	Toronto Word Poll recall	
Loprinzi, Koehler et al., 2019 (US) [47]	122	21.2	50% F, 50% M	15 mins	Low Moderate	Treadmill	Rest	Before After	Between group	Free recall (story)	Logical Memory Task	45 mins
Ludyga et al., 2018 (Switzerland) [48]	51	21.8 (1.3)	30 F 21 M	15 mins	Moderate	Outdoor running	Reading Task	Before	Crossover, counterbalanced	Free recall (words)	Word list	Immediate 20 mins
McNerney & Radvansky, 2015 (US) [49]	136	19.22 (1.19)	NK	2 mins	Moderate	Indoor running	Sudoku	Before	Between subjects	Cued recall (words) Recognition (sentence)	Paired Associative learning task	Immediate 1 week
	132	19.07 (1.18)						After				

Most, Kennedy, & Petras, 2017 (Australia) [50]	74	19.8	38 F 36 M	5 mins	Moderate	Step ups	Puzzle	Before, After	Between subjects	Cued recall	Paired faces and names	24 hours
	80	19.9	40 F 40 M				Finger tapping on lap	After	Between subjects		Paired faces and names	10 mins
	48	19	31 F 17 M				Finger tapping on lap	After	Within subjects		Abstract forms and names	24 hours
	75	21	58 F 17 M				Finger tapping on lap	After	Between subjects		Abstract forms and names	24 hours
Palmer et al., 2019 (Australia) [51]	59	25.75 (8.31)	33 F 28 M	30 mins	Moderate	Stationary cycle	No exercise	Before, After	3 arm RCT	Cued recall (words)	Paired associative learning task	30 mins
	39	22.9 (5.5)	20 F					Before	Between Group			20 mins
Pesce et al., 2009 (Italy) [52]	52	11-12	NK	60 mins	Mod/High	PE class Circuit training	No exercise	Before	Between subjects	Free recall (words)	Visual word list test	2 mins 12 mins
Piepmeier et al., 2020 (US) [53]	29	21.69	29 M 0 F	To exhaustion	Light High	Cycle ergometer	No exercise	Before	Between subjects	Free recall and recognition (words, spatial location)	RAVLT Spatial memory task	Immediate 30 mins 24 hours
Pyke et al., 2020 (UK) [54]	19	21.85 (2.43)	11 F 8 M	30 mins	Low, Mod, High	Ergonomic bicycle	Passive rest	After	Within subjects	Recognition (word-image)	Words image pared task	80 mins
	17	19.77 (1.27)	10 F 7 M	30 mins	Moderate		Active rest					90 mins
	23	19.62 (1.51)	20 F 3 M	6 mins	Mod, High		Passive rest					90 mins
Salas, Minakata, & Keleman, 2011 (US) [55]	80	19.35 (2.34)	46 F, 34 M	10 mins	Moderate	Walking	Sitting	Before	Between subjects	Free recall (words)	?	Immediate

Schmidt-Kassow et al., 2014 (Germany) [56]	18	22.8 (2.6)	9 F 9 M	30 mins	Low	Treadmill	Encoding while sitting	During	Within subjects	Cued recall (words)	Auditory paired association task	24 hours
	31	21.7 (2.7)	16 F 5 M									
Schramke & Bauer, 1997 (US) [57]	96	20 (young) 69 (old)	NK	5-7 mins	Preferred walking pace	Indoor walk	Seated rest	Before	Between subjects	Free, cued recall and recognition (words)	California Verbal Learning Test	20 mins
Siddiqui & Loprinzi, 2018 (US) [58]	20	21.1 (1)	8 F 12 M	20 mins	Brisk walking pace (moderate)	Treadmill	Sudoku	Before During	Within subjects	Free recall (words)	Deese-Roediger-McDermott Paradigm	Immediate 25 minutes
Slutsky-Ganesh, Etnier, & Labban, 2020 (US) [59]	76	21.6 (3.19)	30.5% M, 69.5% F	20 mins	Moderate	Recumbent bike	No exercise	Before After Before & After	Between subject	Free recall (words)	RAVLT	Immediate 24 hours
	22	22.76 (3.2)	33.2% M 66.8% F									
Sng, Frith, & Loprinzi, 2018 (US) [60]	88	23.3 (3.7)	42 F 46 M	15 mins	Preferred walking pace	Treadmill	Relaxation	Before During After	Between subjects	Free, cued recall and recognition (words) Prospective memory	RAVLT	20 mins 24 hours
Soga, Kamijo, & Masaki, 2017 (Japan) [61]	18	22.3 (2.4)	5 F 13 M	-	Moderate	Cycle Ergometer	Seated rest	During	Within subjects	Recognition (pictures)	Visual picture task	5 mins
Stones & Dawe, 1993 (Canada) [62]	20	84.5	17 F 3 M	NK	Low	Stretching	Watch exercise video	Before	Between group	Cued recall (lexical)	Word fluency with semantic/lexical prompts	Immediate 30 mins

van Dongen et al., 2016 (Netherlands) [63]	72	21.9	48 F 24 M	35 mins	Alternative (high low)	Rest	Rest	After	Between group	Cued recall (object location)	Cued recall memory test	48 hours
Wade & Loprinzi, 2018 (US) [64]	34	20	17 F 17 M	15 mins	Moderate	Treadmill	Rest	Before	Between subject	Recognition (pictures)	IAPS images task	24 hours 7 days 14 days
Wang et al., 2020 (China) [65]	22	21.6 (3)	0 F 22 M	30 mins	Moderate	Cycle ergometer	Rest	Before After	Within subject	Free recall and recognition (pictures)	Free recall and recognition task	Immediate 1 hour 24 hours
Weinberg et al., 2014 (US) [66]	46	20	29 F 17 M	-	High	Isometric dynamometer	Rest	After	Within subjects	Recognition (pictures)	IAPS images task	48 hours
Winter et al., 2007 (Germany) [67]	27	22.2(1.7)	27 M 0 F	40 mins (low impact running) 6 mins (sprints at increasing speeds)	High Low	Track	Rest	Before	Within subjects (randomized crossover)	Cued recall (pictures)	Associative vocab learning task	Immediate 1 week 8 months
Yanes & Loprinzi, 2018 (US) [68]	40	21	NK	15 mins	Moderate	Treadmill	Sudoku	Before	Between subjects (two armed parallel RCT)	Free recall (paragraph)	Paragraph episodic memory task	20 mins 24 hours
Yanes, Frith, & Loprinzi, 2019 (US) [69]	24	20.9(1.8)	12 F 12 M	15 mins	Moderate	Treadmill	Rest	During After	Within subjects (counterbalanced)	Free recall (words)	Word list	-
Zuniga et al., 2019 (US) [70]	30	20.4	20 F 10 M	10 mins	Low	Treadmill	Sitting	Before	Within subjects	Free recall (words)	Word list	5 mins
	57	20	31 F							(metacognition)		

26 M

*Table 3.1***.** Summary characteristics of experiments included in meta-analysis.

3.4.2 Quantitative Analyses

The total number of effects per primary moderating variable are displayed in figure 3.4. Focusing on conditions in which acute bouts of exercise were performed after memory encoding, several moderators influenced long-term episodic memory. Performance differed as a function of participant’s age, with young adults showing improved memory performance while the opposite was true for older adults. Our results indicated that older adults’ memory performance did not improve before, during, or after acute bouts of exercise.

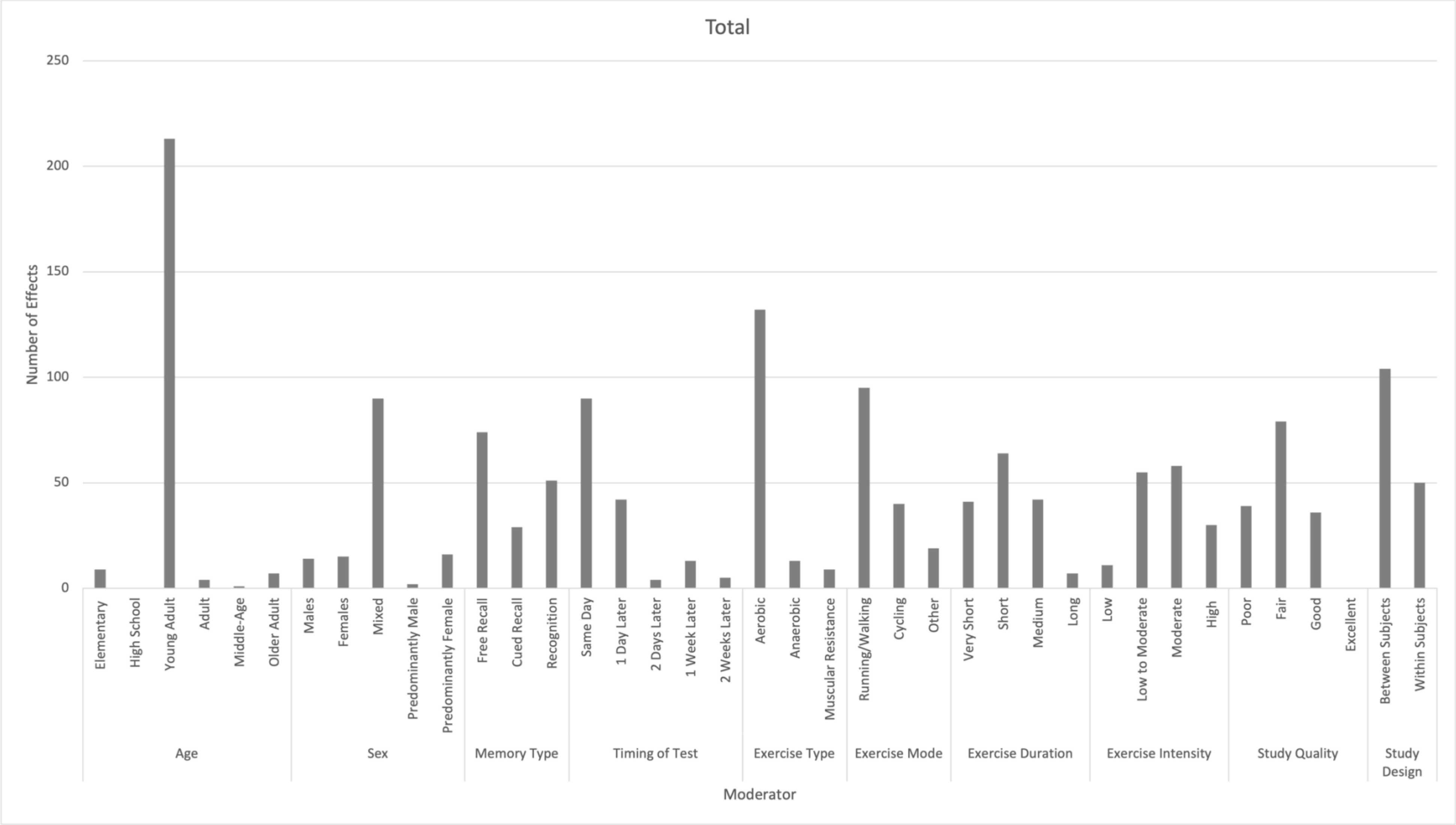


Figure 3.4. Total number of effects for each moderator

3.4.3 Exercise Before Encoding

The overall effect size for exercise before memory encoding compared to control conditions was d = 0.23 (95% CI: [0.13, 0.34], $p < 0.001$; Table 3.2, Figure 3.5), which constitutes a small effect size. There was evidence of a significant moderating effect for the analysis [Q = 317.17, df (92), $p < 0.001$, $I^2 = 70.81$]. For the primary moderator of interest, free-recall (d = 0.40, 95% CI: [0.27, 0.53], $p < 0.001$) memory was improved significantly. Cued-recall (d = 0.077, 95% CI [−0.267, 0.421]) and recognition memory (d = −0.057, 95% CI [−0.207, 0.092]) were not significantly influenced. Analyses of moderators of secondary interest revealed that elementary school children's (d = 0.70, 95% CI: [0.37, 1.03], $p < 0.001$) and young adults' (d = 0.19, 95% CI: [0.09, 0.30], $p < 0.001$) episodic memory improved, while older adults' (d = −0.47, 95% CI: [−0.89, −0.06], p = 0.03) memory performance declined significantly. Additionally, significant improvements in episodic memory were detected when mixed-sex samples were measured (d = 0.37, 95% CI [0.01, 0.23], $p < 0.001$), memory testing occurred on the same day as encoding (d = 0.30, 95% CI [0.17, 0.43], $p < 0.001$), and when exercise parameters included aerobic protocols (d = 0.24, 95% CI [0.12, 0.35], $p < 0.001$), cycling modality (d = 0.61, 95% CI [0.39, 0.84], $p < 0.001$), medium duration (d = 0.64, 95% CI[0.43, 0.85], $p < 0.001$), and moderate intensity (d = 0.56, 95% CI [0.38, 0.74], $p < 0.001$). The regression intercept for the Egger's test (intercept 1.90, p = 0.002) was statistically significant, indicative of publication bias.

Reinforcing the findings of the primary search, the secondary search indicated that exercise before encoding led to the largest mnemonic benefits in studies by Etnier et al. (2020), Etnier et al. (2021), McSween et al. (2021), and Schmid et al. (2023).

	Number of ES contributions	ES (Cohen's d)	Lower CI	Upper CI	*p*-value	Q-value	*p*-value
Age						20.679	<0.001
Elementary	6	0.701***	0.372	1.030	<0.001		
High School	-	-	-	-	-		
Young Adult	80	0.19***	0.092	0.295	<0.001		
Adult	3	1.236	-0.302	2.774	0.115		
Middle-Age	-	-	-	-	-		
Older Adult	4	-0.474*	-0.892	-0.057	0.026		
Sex						26.077	<0.001
Males	11	0.265	-0.014	0.545	0.063		
Females	15	-0.204*	-0.379	0.090	0.022		
Mixed	46	0.374***	0.005	0.233	<0.001		
Predominantly Male	-	-	-	-	-		
Predominantly Female	12	0.178*	0.005	0.351	0.044		
Memory Type						20.564	<0.001
Free Recall	56	0.399***	0.267	0.531	<0.001		
Cued Recall	8	0.077	-0.267	0.421	0.660		
Recognition	29	-0.057	-0.207	0.092	0.452		
Timing of Test						2.969	0.397
Same Day	60	0.299***	0.171	0.427	<0.001		
1 Day Later	19	0.107	-0.134	0.348	0.384		
2 Days Later	-	-	-	-	-		
1 Week Later	9	0.101	-0.354	0.556	0.663		
2 Weeks Later	5	0.116***	0.171	0.427	<0.001		
Exercise Type						3.479	0.176
Aerobic	82	0.236***	0.124	0.349	<0.001		
Anaerobic	5	0.470	-0.055	0.995	0.079		
Muscular Resistance	6	-0.058	-0.400	0.285	0.741		
Exercise Mode						13.37	0.001

Running/Walking	64	0.195**	0.066	0.324	0.022		
Cycling	17	0.610***	0.385	0.835	<0.001		
Other	12	0.292	-0.047	0.631	0.091		
Exercise Duration						22.951	<0.001
Very Short	19	0.200	-0.041	0.440	0.104		
Short	52	0.079	-0.041	0.198	0.198		
Medium	18	0.638***	0.430	0.846	<0.001		
Long	4	0.694*	0.056	1.33	0.033		
Exercise Intensity						24.852	<0.001
Low	7	0.345**	0.138	0.552	0.001		
Low to Moderate	36	-0.018	-0.186	0.149	0.832		
Moderate	30	.563***	0.382	0.743	<0.001		
High	20	0.120	-0.026	0.266	0.106		
Study Quality						9.212	0.010
Poor	19	0.544**	0.309	0.779	<0.001		
Fair	45	0.129	-0.027	0.285	0.105		
Good	29	0.161*	0.016	0.306	0.030		
Excellent							
Study Design						16.794	<0.001
Between Subjects	66	0.083	-0.055	0.222	0.238		
Within Subjects	27	0.506***	0.359	0.653	<0.001		

* Indicates statistically significant effect size ($p < 0.05$), ** ($p < 0.01$), *** ($p < 0.001$)

Table 3.2. Moderation results for exercise before memory encoding vs. control

Exercise Before

Study name	Statistics for each study			
	Std diff in means	Lower limit	Upper limit	p-Value
Austin 2019	0.105	-0.334	0.545	0.638
Coles 2008	1.343	0.706	1.979	0.000
Dilley 2019	-0.237	-0.859	0.385	0.454
Dillley 2019a	-0.238	-0.860	0.384	0.454
Etnier 2014	0.390	-0.217	0.998	0.208
Etnier 2014a	0.156	-0.446	0.759	0.611
Haynes 2019b	0.137	-0.264	0.539	0.503
Haynes 2019c	0.059	-0.342	0.459	0.773
Johnson 2019	0.129	-0.273	0.530	0.530
Labban 2011a	1.040	0.302	1.779	0.006
Labban 2018a	0.824	0.239	1.410	0.006
Labban 2018b	0.933	0.326	1.539	0.003
Labban 2018e	0.602	0.052	1.153	0.032
Loprinzi 2019b	-0.209	-0.847	0.428	0.520
Loprinzi 2019c	-0.818	-1.480	-0.156	0.015
Loprinzi 2019d	-0.073	-0.709	0.563	0.822
Loprinzi 2019e	-0.105	-0.741	0.532	0.747
Loprinzi 2019f	0.179	-0.442	0.800	0.573
Loprinzi 2019g	0.123	-0.497	0.744	0.697
Loprinzi 2019h	0.417	-0.209	1.044	0.192
Loprinzi 2019i	0.235	-0.387	0.857	0.459
Loprinzi 2019j	0.188	-0.433	0.809	0.553
Loprinzi 2019k	0.302	-0.330	0.933	0.349
Loprinzi 2019l	0.114	-0.515	0.742	0.723
Loprinzi 2019m	0.082	-0.555	0.718	0.801
Loprinzi 2019n	-0.100	-0.736	0.536	0.758
Loprinzi 2019o	0.286	-0.337	0.909	0.369
Loprinzi 2019p	0.595	-0.038	1.228	0.066
Loprinzi 2019q	0.654	0.018	1.290	0.044
Loprinzi 2020	-0.591	-1.224	0.043	0.068
Loprinzi 2020a	-0.489	-1.118	0.140	0.128
Loprinzi 2020b	0.534	-0.140	1.209	0.121
Loprinzi 2020c	0.166	-0.498	0.830	0.623
Loprinzi 2020d	0.036	-0.638	0.709	0.917
Loprinzi 2020e	0.073	-0.601	0.747	0.832
Ludgya 2018	0.293	0.013	0.574	0.040
McNerny 2015	0.000	-0.336	0.336	1.000
McNerny 2015a	1.527	1.145	1.909	0.000
Most 2017b	-0.403	-1.063	0.257	0.231
Palmer 2019a	1.496	0.765	2.227	0.000
Pesce 2009	0.471	0.184	0.757	0.001
Pesce 2009a	1.234	0.873	1.595	0.000
Pesce 2009b	0.580	0.287	0.874	0.000
Pesce 2009c	1.158	0.807	1.509	0.000
Piepmeier 2020	-0.105	-0.962	0.752	0.810
Piepmeier 2020a	0.105	-0.806	1.016	0.821
Piepmeier 2020b	-0.403	-1.268	0.462	0.361
Piepmeier 2020c	-0.075	-0.986	0.836	0.871
Piepmeier 2020d	-0.226	-1.085	0.633	0.606
Piepmeier 2020e	0.665	-0.270	1.600	0.163
Salas 2011a	0.400	-0.214	1.014	0.201
Schramke 1997c	-0.677	-1.499	0.146	0.107
Schramke 1997d	-0.501	-1.314	0.311	0.227
Schramke 1997e	-0.777	-1.607	0.053	0.066
Schramke 1997i	-0.202	-1.005	0.600	0.621
Schramke 1997j	-0.151	-0.953	0.650	0.711
Schramke 1997k	0.283	-0.521	1.087	0.491
Slutsky 2020a	0.552	-0.096	1.200	0.095
Sng 2017b	2.418	1.640	3.195	0.000
Sng 2017c	-0.158	-0.749	0.434	0.602
Stones 1993	0.126	-0.751	1.004	0.778
Wade 2018	-0.246	-0.921	0.429	0.475
Wade 2018a	-0.109	-0.781	0.564	0.752
Wade 2018b	-0.074	-0.747	0.598	0.829
Wade 2018c	-0.595	-1.282	0.092	0.090
Wade 2018d	-0.448	-1.129	0.233	0.197
Wade 2018e	0.142	-0.531	0.816	0.678
Wade 2018f	-0.593	-1.279	0.094	0.091
Wade 2018g	-0.273	-0.948	0.403	0.429
Wade 2018h	0.300	-0.376	0.976	0.384
Wade 2018i	-0.496	-1.178	0.187	0.155
Wade 2018j	-0.151	-0.824	0.522	0.660
Wade 2018k	0.103	-0.569	0.776	0.763
Wade 2018l	-0.727	-1.421	-0.033	0.040
Wade 2018m	-0.085	-0.758	0.587	0.804
Wade 2018n	0.111	-0.562	0.784	0.746
Yanes 2018	0.351	-0.273	0.976	0.270
Yanes 2018a	0.276	-0.347	0.899	0.385
Siddiqui 2018	0.844	0.333	1.354	0.001
Kao 2018	0.283	-0.050	0.616	0.096
Kao 2018a	0.467	0.123	0.811	0.008
Zuniga 2019	0.381	0.004	0.758	0.047
Zuniga 2019a	0.239	-0.136	0.615	0.212
Zuniga 2019b	0.624	0.145	1.103	0.011
Zuniga 2019c	0.675	0.190	1.161	0.006
Yanes 2019a	-0.171	-0.574	0.232	0.405
Loprinzi 2020x	0.731	0.271	1.191	0.002
Wang 2020c	0.553	0.057	1.049	0.029
Wang 2020d	0.760	0.235	1.284	0.005
Wang 2020e	0.859	0.319	1.400	0.002
Winter 2007	0.425	0.031	0.818	0.035
Winter 2007a	-0.214	-0.596	0.167	0.271
Frith 2017	0.813	0.199	1.428	0.010
	0.234	0.126	0.341	0.000

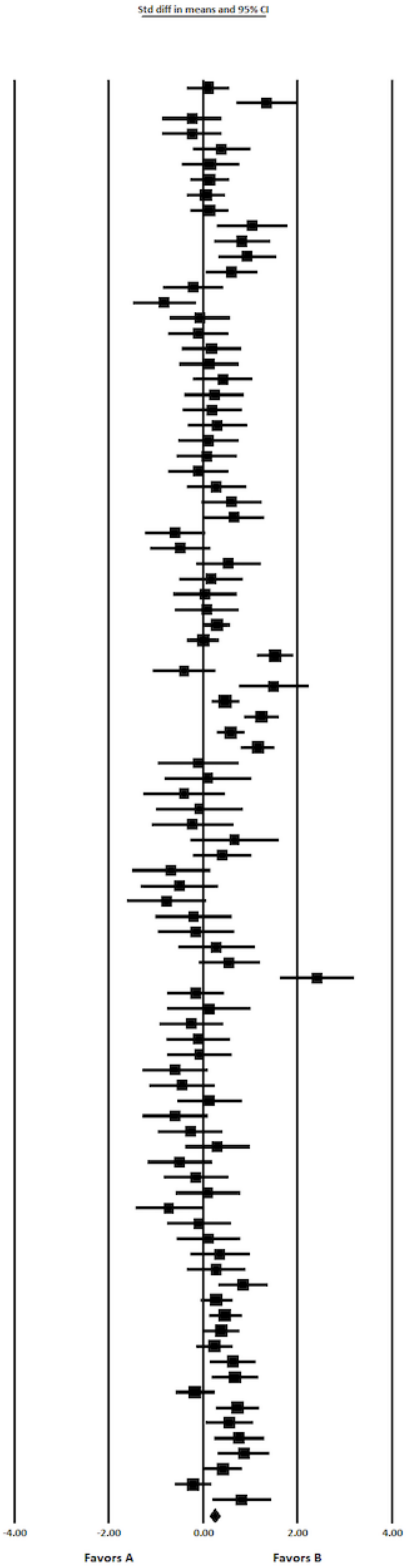


Figure 3.5. Forest plot indicating effect sizes for exercise before memory encoding

3.4.4 Exercise After Encoding

The overall effect size for exercise bouts performed following memory encoding compared to control conditions was d = 0.33 (95% CI [0.89, 0.56], p = 0.007; Table 3.3, Figure 3.6), which constitutes a small-to-medium effect size. There was evidence of significant moderation effects [Q = 440.37, df (48), p < 0.001, I^2 = 89.10]. For the primary moderator of interest, recognition memory significantly improved when exercise occurred following memory encoding (d = 0.623, 95% CI [0.12, 1.13], p = 0.015), while free-recall (d = 0.194, 95% CI [−0.16, 0.55], p = 0.283), and cued-recall (d = 0.142, 95% CI [−0.22, 0.51], p = 0.448) memory processes were not significantly influenced. Analyses of moderators of secondary interest revealed that young adults' memory function improved (d = 0.43, 95% CI [0.18, 0.68], p = 0.001) while older adults' episodic memory performance declined (d = −0.94, 95% CI [−1.43, −0.45, p < 0.001). Other moderators that significantly influenced episodic memory function were detected when samples were predominantly female (d = 1.15, 95% CI [0.44, 1.85], p = 0.001) and exercise parameters included resistance exercise (d = 2.68, 95% CI [1.99, 3.37], p < 0.001), long duration exercise (d = 2.68, 95% CI [1.99, 3.37], p < 0.001), and moderate intensity (d = 0.81, 95% CI: [0.43, 1.18], p < 0.001). The regression intercept for the Egger's test (intercept 0.71, p = 0.67) was not statistically significant, indicating that there was no evidence of publication bias in this set of studies. Through the secondary search, Loprinzi (2019) found null results, and Zabriskie and Heath (2019) found that exercise during encoding benefitted free recall memory more than exercise before encoding.

	Number of ES contributions	ES (Cohen's d)	Lower CI	Upper CI	p-value	Q-value	p-value
Age						24.269	<0.001
Elementary	2	-0.041	-0.477	0.394	0.852		
High School	-	-	-	-	-		
Young Adult	43	0.427**	0.175	0.680	0.001		
Adult	1	0	-0.591	0.591	1		
Middle-Age	-	-	-	-	-		
Older Adult	3	-0.938***	-1.427	-0.449	<0.001		
Sex						5.881	0.118
Males	3	0.207	-0.266	0.681	0.390		
Females	-	-	-	-	-		
Mixed	34	0.259*	0.025	0.494	0.030		
Predominately Male	-	-	-	-	-		
Predominately Female	4	1.146**	0.439	1.852	0.001		
Memory Type						2.534	0.282
Free Recall	15	0.194	-0.160	0.549	0.283		
Cued Recall	16	0.142	-0.224	0.507	0.448		
Recognition	18	0.623*	0.120	1.126	0.015		
Timing of Test						8.137	0.043
Same Day	25	0.136	-0.129	0.401	0.314		
1 Day Later	16	0.067	-0.166	0.300	0.573		
2 Days Later	4	2.015*	0.442	3.588	0.012		
1 Week Later	4	1.035	-0.123	2.193	0.080		
2 Weeks Later	-	-	-	-	-		
Exercise Type						59.307	<0.001
Aerobic	41	0.056	-0.113	0.224	0.517		
Anaerobic	5	1.235**	0.459	2.011	0.002		
Muscular Resistance	3	2.681***	1.993	3.369	<0.001		

Exercise Mode						7.327	0.026
Running/Walking	21	0.058	-0.370	0.486	0.791		
Cycling	21	0.256	-0.003	0.515	0.052		
Other	7	1.312	0.504	2.120	0.001		
Exercise Duration						54.535	<0.001
Very Short	17	0.439	-0.015	0.894	0.058		
Short	8	-0.041	-0.517	0.435	0.866		
Medium	21	0.058	-0.117	0.233	0.515		
Long	3	2.681***	1.993	3.369	<0.001		
Exercise Intensity						26.696	<0.001
Low	2	-0.450*	-0.829	-0.071	0.020		
Low to Moderate	14	-0.275	-0.620	0.070	0.118		
Moderate	23	0.805***	0.431	1.179	<0.001		
High	10	0.219	-0.114	0.552	0.198		
Study Quality						27.369	<0.001
Poor	18	1.061***	0.605	1.518	<0.001		
Fair	24	-0.196	-0.407	0.015	0.068		
Good	7	0.293**	0.079	0.506	0.007		
Excellent							
Study Design						0.100	0.752
Between Subjects	33	0.291	-0.059	0.641	0.103		
Within Subjects	16	0.363*	0.086	0.64	0.010		

* Indicates statistically significant effect size ($p < 0.05$), ** ($p < 0.01$), ***($p < 0.001$)

Table 3.3. Moderation results for exercise after memory encoding vs. control

Exercise After

Study name	Statistics for each study			
	Std diff in means	Lower limit	Upper limit	p-Value
Delancey 2018	0.474	-0.154	1.103	0.139
Haynes 2019	0.000	-0.400	0.400	1.000
Haynes 2019a	-0.147	-0.549	0.256	0.475
Hotting 2016	-0.555	-1.099	-0.011	0.046
Hotting 2016a	-0.271	-0.807	0.266	0.323
Hotting 2016b	-0.554	-1.093	-0.015	0.044
Hotting 2016c	-0.348	-0.881	0.185	0.200
Jentsch 2020	0.269	-0.300	0.838	0.354
Jentsch 2020a	0.000	-0.566	0.566	1.000
Jentsch 2020b	0.296	-0.274	0.865	0.309
Labban 2011	0.237	-0.459	0.932	0.505
Labban 2018	0.384	-0.141	0.908	0.151
Labban 2018c	0.167	-0.342	0.677	0.520
Labban 2018d	0.268	-0.248	0.783	0.309
Lind 2018	-0.035	-0.626	0.556	0.907
Lind 2018a	-0.049	-0.693	0.595	0.882
Loprinzi 2019	0.434	-0.163	1.032	0.154
Loprinzi 2019a	0.162	-0.430	0.754	0.591
McNerny 2015b	2.313	1.873	2.754	0.000
McNerny 2015c	1.833	1.427	2.240	0.000
Most 2017	0.056	-0.201	0.314	0.667
Most 2017a	0.904	0.237	1.572	0.008
Most 2017c	0.289	-0.152	0.730	0.198
Most 2017d	0.208	-0.246	0.662	0.369
Palmer 2019	0.000	-0.591	0.591	1.000
Salas 2011	0.065	-0.543	0.672	0.835
Schramke 1997	-0.598	-1.416	0.220	0.152
Schramke 1997a	-0.933	-1.776	-0.091	0.030
Schramke 1997b	-1.342	-2.227	-0.456	0.003
Schramke 1997f	0.110	-0.691	0.910	0.789
Schramke 1997g	-0.492	-1.304	0.320	0.235
Schramke 1997h	-0.333	-1.139	0.472	0.417
Slutsky 2020	0.198	-0.432	0.827	0.538
Sng 2017	1.025	0.397	1.654	0.001
Sng 2017a	-1.916	-2.630	-1.202	0.000
Van Dongen 2016	-0.027	-0.592	0.539	0.926
Weinberg 2014	3.480	2.564	4.396	0.000
Weinberg 2014a	2.308	1.562	3.054	0.000
Weinberg 2014b	2.391	1.635	3.148	0.000
Pyke 2020	0.758	0.294	1.222	0.001
Pyke 2020a	1.238	0.695	1.781	0.000
Pyke 2020b	-0.440	-0.938	0.058	0.083
Pyke 2020c	1.274	0.634	1.914	0.000
Pyke 2020d	0.404	-0.021	0.829	0.062
Pyke 2020e	2.452	1.634	3.270	0.000
Yanes 2019	-0.422	-0.840	-0.005	0.048
Wang 2020	-0.060	-0.522	0.402	0.799
Wang 2020a	0.000	-0.462	0.462	1.000
Wang 2020b	0.723	0.204	1.241	0.006
	0.325	0.089	0.561	0.007

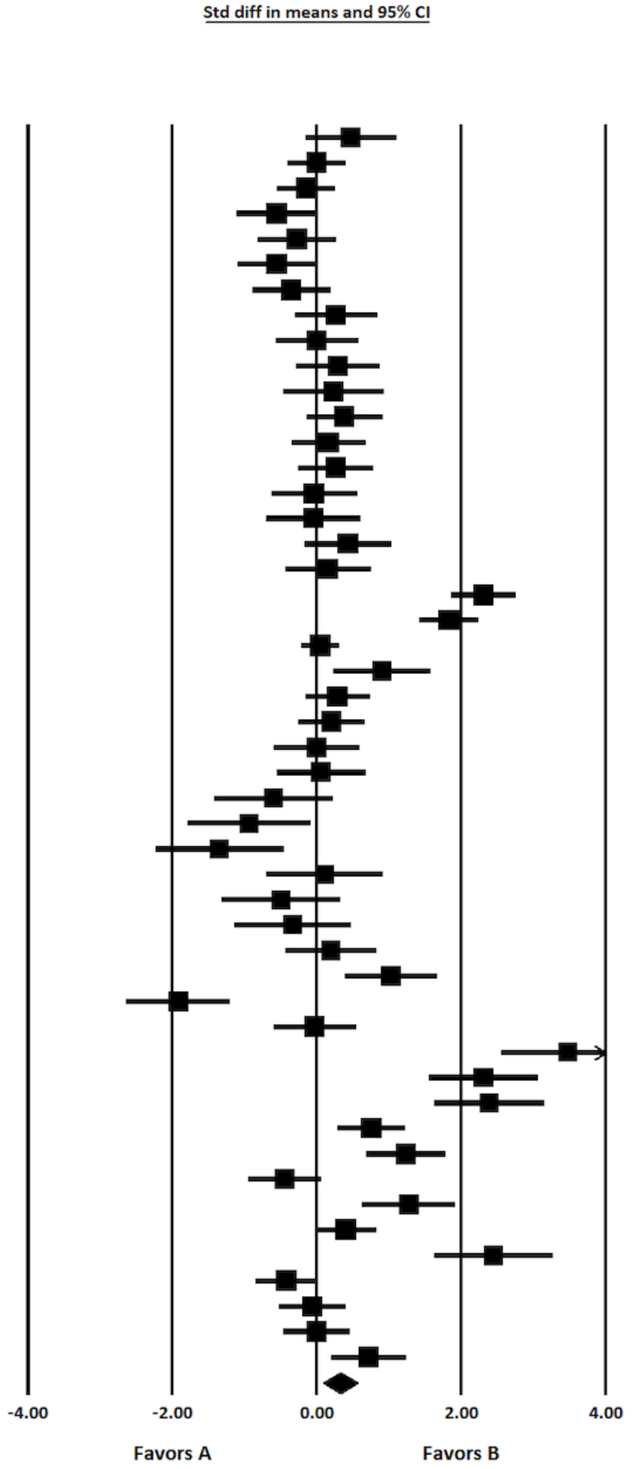


Figure 3.6. Forest plot indicating effect sizes for exercise after memory encoding

3.4.5 Exercise During Encoding

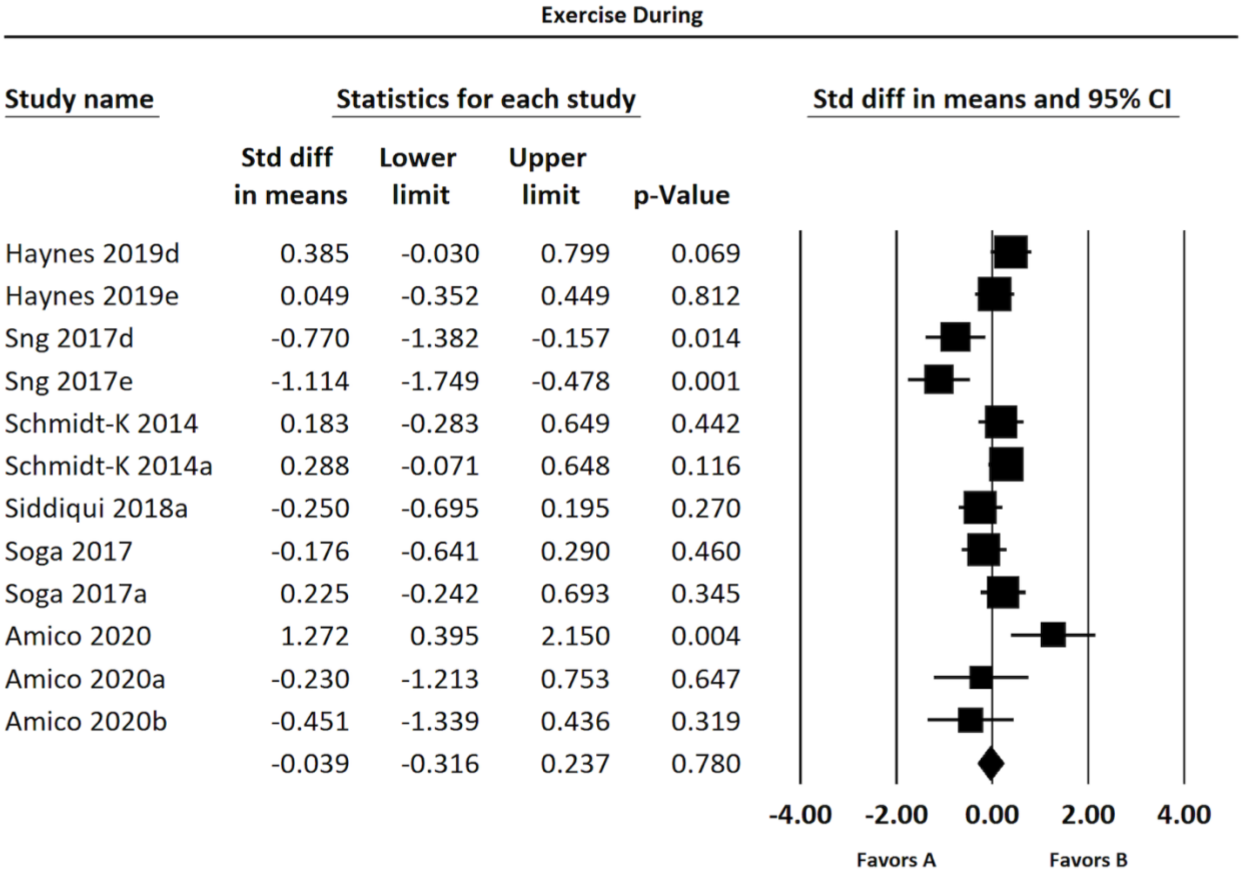
The overall effect size for exercise performed during memory encoding compared to control conditions was non-significant d = −0.04 (95% CI [−0.31, 0.24], p = 0.78; Table 3.4, Figure 3.7). There was evidence of a significant moderation effect (Q = 36.21, df (11), $p < 0.001$, $I^2 = 69.62$). Moderator analyses yielded one significant result. The effect of participants' age on episodic memory was greatest for elementary-aged children (d = 1.272, CI [0.395, 2.15], p = 0.004). The regression intercept for the Egger's test (intercept −1.62, p = 0.40) was not statistically significant, indicating that there was no evidence of publication bias.

	Number of ES contributions	ES (Cohen's d)	Lower CI	Upper CI	*p*-value	Q-value	*p*-value
Age						8.853	0.012
Elementary	1	1.272**	0.395	2.15	0.004		
High School							
Young Adult	10	-0.018	-0.167	0.131	0.453		
Adult							
Middle-Age	1	-0.230	-1.213	0.753	0.647		
Older Adult							
Sex						0.095	0.757
Males	-	-	-	-	-		
Females	-	-	-	-	-		
Mixed	10	-0.057	-0.394	0.28	0.739		
Predominately Male	2	0.024	-0.369	0.417	0.904		
Memory Type						2.207	0.332
Free Recall	3	-0.181	-0.814	0.451	0.574		
Cued Recall	5	0.232	-0.189	0.653	0.280		
Recognition	4	-0.212	-0.699	0.275	0.394		
Timing of Test						0.087	0.768
Same Day	5	-0.085	-0.451	0.281	0.650		
1 Day Later	7	-0.224	-0.437	0.439	0.996		
2 Days Later	-	-	-	-	-		
1 Week Later	-	-	-	-	-		
2 Weeks Later	-	-	-	-	-		
Exercise Type						0.253	0.615
Aerobic	9	-0.083	-0.365	0.199	0.563		
Anaerobic	3	0.206	-0.885	1.297	0.711		
Muscular Resistance							
Exercise Mode						0.095	0.757

Running/Walking	10	-0.057	-0.394	0.28	0.739		
Cycling	2	0.024	-0.369	0.417	0.904		
Other							
Exercise Duration						1.394	0.498
Very Short	5	0.116	-0.376	0.607	0.644		
Short	4	-0.324	-0.970	0.323	0.326		
Medium	3	0.089	-0.235	0.413	0.590		
Long							
Exercise Intensity						3.572	0.168
Low	2	0.249	-0.035	0.533	0.086		
Low to Moderate	5	-0.297	-0.786	0.193	0.234		
Moderate	5	0.116	-0.376	0.607	0.644		
High							
Study Quality						0.095	0.757
Poor	2	0.024	-0.369	0.417	0.904		
Fair	10	-0.057	-0.279	0.233	0.739		
Good							
Excellent							
Study Design						1.003	0.317
Between Subjects	5	-0.294	-1.075	0.488	0.461		
Within Subjects	7	0.115	-0.059	0.290	0.194		

* Indicates statistically significant effect size ($p < 0.05$), ** ($p < 0.01$), *** ($p < 0.001$)

Table 3.4. Moderation results for exercise during memory encoding vs. control



Exercise During

Study name	Std diff in means	Lower limit	Upper limit	p-Value
Haynes 2019d	0.385	-0.030	0.799	0.069
Haynes 2019e	0.049	-0.352	0.449	0.812
Sng 2017d	-0.770	-1.382	-0.157	0.014
Sng 2017e	-1.114	-1.749	-0.478	0.001
Schmidt-K 2014	0.183	-0.283	0.649	0.442
Schmidt-K 2014a	0.288	-0.071	0.648	0.116
Siddiqui 2018a	-0.250	-0.695	0.195	0.270
Soga 2017	-0.176	-0.641	0.290	0.460
Soga 2017a	0.225	-0.242	0.693	0.345
Amico 2020	1.272	0.395	2.150	0.004
Amico 2020a	-0.230	-1.213	0.753	0.647
Amico 2020b	-0.451	-1.339	0.436	0.319
	-0.039	-0.316	0.237	0.780

Figure 3.7. Forest plot indicating effect sizes for exercise during memory encoding

3.5 Discussion

The primary finding of this meta-analytic review is that acute bouts of exercise performed prior to or following encoding have selective effects on episodic memory processes. We assessed 42 primary research studies and our main findings indicated that performance on free-recall tests of memory significantly improved (d = 0.399) more than either cued-recall (d = 0.077) or recognition (d = −0.05) tests of memory when exercise preceded memory encoding. Exercise performed following encoding had a greater impact on recognition memory performance (d = 0.623) than on either free- (d = 0.194) or cued-recall (d = 0.142) performance. A secondary narrative review affirmed the findings of the former meta-analysis. Contemporary psychological theories of memory and recent advances in the study of the neurophysiology of memory systems provide the means to explain why exercise has selective effects on memory processes.

When exercise preceded encoding, there was a significant improvement in memory performance (d = 0.29), with the greatest effect exhibited on free-recall processes. Conceptually, free- recall memory is an issue of item remembrance, which can be viewed as the developing strength of a memory trace (Malmberg et al., 2019). Remembering items for later recall is influenced by a wide variety of factors which have been studied extensively. Theories of Levels of Processing (Amico and Schaefer, 2020), strategy utilization (Craik and Lockhart, 1972), mental engagement (Coles and Tomporowski, 2008; Kahneman, 1973; Hockey et al., 1986), and other cognitive constructs have addressed conditions that affect the degree to which individuals allocate attentional resources to environmental events. Physical exercise has also been hypothesized to influence attentional allocation. From the perspective of psychological theory, Audiffren (McMorris et al., 2009) proposed that the energetic property of acute bouts of exercise influences attentional processes and may augment memory storage processes. Energetics theory assumes three interrelated processes: cognition, which reflects an individual’s knowledge and skills; affection, which reflects feelings and emotions; and conation, which is the willingness, or motivation, to expend physical and mental effort to perform (Delancey et al., 2019; Haynes and Loprinzi, 2019; Hilgard, 1980; Spirduso et al., 2007). From the neurophysiological perspective, several researchers propose that exercise prior to encoding leads to elevations of brain catecholamines, which presumably increase attention by altering neural signal-to-noise conditions, and by brain-derived neurotrophic factors (BDNF) (Etnier et al., 2014; Hötting et al., 2016; Dilley et al., 2019; Gomez-Pinilla and Hillman, 2013) and growth factors (Loprinzi, 2019). A comprehensive description of brain structures and pathways involved in episodic memory processes and how they may be affected by acute bouts of exercise has been provided by Loprinzi et al. (2017). A meta-analytic review of studies conducted with adults found that moderately intense warm-up exercises had a small positive effect on learning while high-intensity exercise had a substantial negative effect (Johnson et al., 2019; McMorris et al., 2015). The authors of a recent meta-analysis of acute exercise experiments that focused on motor learning drew similar conclusions. Wanner et al. (2020) hypothesize that exercise performed prior to practicing motor tasks influence motor performance by optimizing movement planning, which relies heavily on the allocation of cognitive resources. Psychological theory and neurophysiological research may explain how acute bouts of exercise engage executive processes and control of operations of prefrontal cortical networks that select and weigh the importance of encoded information. Drawing upon the Search of Associative Memory model, exercise prior to encoding appears to alter the sampling and search processes that are involved in free- recall memory. This explanation is in line with those expressed in the contextual-binding model (Yonelinas et al., 2019), which hypothesizes that hippocampal structures are central to item- context associations and activations that influence recollection.

Episodic memory was improved when exercise occurred following encoding (d = 0.37). Bouts of exercise enhanced performance on recognition memory tests more than free- or cued-recall tests. Viewed from a psychological perspective, recognition is an issue of item familiarity and involves making a rational response based on the weight of an item and context trace strength via a Bayesian process, which is a reasonable expectation based on past knowledge (Kao et al., 2018; Shiffrin and Steyvers, 1997). Recognition involves discrimination between items that belong to a target population and items that belong to a non-target population (Labban and Etnier, 2011; Green and Swets, 1974). The probability of responding to targets (hits) and responding to non-targets (false alarms) provide the basis for Receiver Operating Curve analyses, which can be applied to the study of recognition memory (Labban and Etnier, 2018; Stanislaw and Todorov, 1999). Studies of attention reveal that the likelihood of hits and false alarms in a given task are affected by a variety of factors (e.g., cost/benefits, ratio of target to non-target items, personal beliefs, and arousal states) (Lind et al., 2019; Warm, 1984). Acute exercise temporarily alters individuals' response bias when performing decision-making tasks (Loprinzi et al., 2021). Exercise- induced shifts in participant's bias would be expected to influence performance on tests of recognition memory. Neurophysiological models of long-term memory propose that item familiarity is altered by emotional arousal and the biological stress response when exercise follows encoding, which is characterized by a cascade of neurohormonal changes (Loprinzi et al., 2019a,b, 2020a,b, 2021; McGaugh, 2000, 2004, 2018). The release of adrenal stress hormones results in widespread changes throughout the peripheral and central nervous system. In particular, the stress hormones epinephrine and cortisol are implicated in memory consolidation. Considerable evidence obtained from animal studies indicates that systemic administration of stimulant drugs, epinephrine, glucose, and cortisol can enhance memory (see reviews by Cahill and McGaugh, 1998; Gold et al., 2001; McGaugh, 2015). Exercise- induced stress responses have also been shown to influence human memory storage (Segal et al., 2012). Much of the consolidation process research has focuses on the bi-directional relation between the amygdala and hippocampus (Loprinzi et al., 2017). The Wanner et al. (2020) review of experiments that focused on motor learning reached similar conclusions. They propose that exercise performed following encoding enhances learning via consolidation and neuroplasticity processes, as opposed to arousal, attention, or energetic processes. Together, psychological theory and neurophysiological research may explain how acute bouts of exercise engage hippocampal processes and the storage of episodic memories. Drawing upon the Retrieving Effectively from Memory model, exercise following encoding appears to impact individual's response bias during recognition memory tests. Drawing on the Contextual-Binding model (Yonelinas et al., 2019), tests of recognition memory involve not only the recognition of an item but also the retrieval of past memory of contexts in which the item was initially acquired. The perirhinal cortex is hypothesized to play the pivotal role for familiarity-based recognition. Brain lesion studies have also provided evidence that the function of the medial temporal lobe is not unitary. Because the medial temporal lobe differentially influences recollection (free-recall) and familiarity (recognition) of items, it provides a dual-process model (Bowles et al., 2010). Our findings are in line with the dual-processing model of the medial temporal lobe as we present a clear distinction between free-recall and recognition memory processes. When exercise follows encoding the consolidation of memory for items may increase the strength of item representation.

Regardless of the temporal relation between exercise and encoding, the strength of the effect of exercise on cued-recall test performance was found to range between very small and small (d = 0.077 when exercise preceded encoding; d = 0.142 when exercise followed encoding, d = 0.232 when exercise occurred during encoding). Cued-recall memory tests are viewed as a hybrid between free-recall and recognition tests (Pesce et al., 2009; Wilson and Criss, 2017; Piepmeier et al., 2020). Free-recall performance depends on self-generated cues and available context cues; recognition performance depends on researcher-generated cues and the participant's available context cues. Cued-recall is similar to free recall in that the individual must generate a target cue that is employed during memory search. Cued-recall is also similar to recognition in that an item cue is provided to the participant. A series of experiments conducted by Wilson and Criss (2017) using cued-recall methods provide data that support predictions from the SAM and REM models. They hypothesize that a cue comes to be associated with a specific target item when a list of cue-target pairs is presented; however, the cue also comes to be associated with other target items on the list. Interference due to mismatches between cues and targets with different trace strengths leads to confusion and results in changes in response bias for memory traces during the search process (Pyke et al., 2020). Prior research using cued-recall methods reveals that test performance is altered via manipulating some list variables, such as word frequency, but not by others, such as context variability (Criss et al., 2011). The findings of the present reviews suggest that acute bouts of exercise performed following encoding has a slightly greater impact on the processes involved in cued-recall test performance than exercise performed prior to encoding. The lack of strong evidence for the relation between exercise and cued-recall memory may be explained via the context-binding model, which hypothesizes that while the pathways that impact recognition and familiarity are distinct, they merge within the medial temporal lobe of the neocortex. The reciprocal relations that exists within neocortical and deeper brain structures result in considerable overlap in the subjective evaluation of memory of past experiences (Eichenbaum et al., 2007).

Since the initial research conducted over a century ago by Yerkes and Dodson (1908), there has been a longstanding interest in the relationship between arousal and memory. The results of the present review suggest that acute bouts of exercise provide an ideal model to advance general theories of memory and learning. Via the systematic manipulation of the temporal relation between exercise and encoding, as well as quantitative and qualitative aspects of exercise, researchers may derive a clearer understanding of brain structures involved in memory as well as psychological and environmental factors that may moderate memory storage and retrieval during recall and recognition tests.

The results of the present review suggest that long-term episodic memory is not influenced by exercise when performed simultaneously with encoding ($d = -0.04$). This finding differs from the conclusion drawn by Loprinzi et al. (2019a), who found that exercise performed under dual-task conditions significantly impaired long-term encoding ($d = -0.23$). The lack of agreement may be due to including the results of several recently published experiments that found that treadmill walking and ergometer cycling (Schramke and Bauer, 1997; Schmidt-Kassow et al., 2014, 2013, 2010) resulted in improvements on tests of long-term memory for words. Alternatively, the lack of clarity may be due to the complexities of dual-task performance and learning. The mental operations that underlie dual-task performance have been studied extensively and several theories have been proposed to explain how individuals optimize decision making when placed in conditions in which they simultaneously perform a motor-movement task (e.g., walking) and a cognitive task (e.g., encoding a word list) (see historical review by Wickens, 2008). Under these conditions, cognitive-motor interference may occur. However, the interference between motoric activities and encoding depends on several factors. A task-classification system developed by Plummer et al. (2013) describes nine dual-task conditions and possible outcomes ranging from no interference, to mutual facilitation, to mutual deterioration, to tradeoffs that differentially impact motor performance and cognitive performance (see reviews by Dietrich and Audiffren, 2011; Tomporowski and Qazi, 2020). Thus, there may be specific dual-task conditions in which the encoding of episodic information into long-term memory may be lessened, enhanced, or have null effects.

A series of experiments conducted recently with children provides insights into dual-task conditions that may facilitate encoding and long-term memory. They may also help explain children's enhanced memory performance found in our meta- analysis. We found that children's memory performance was enhanced when exercise was performed prior to and simultaneously with encoding. These experiments involved teaching children academic material over several training sessions and, as such, were not included in our review. A prototypical experiment conducted by Schmidt et al. (2019) targeted elementary-age children who were instructed to associate foreign animal words with known animal words during four brief teaching sessions that were distributed over 2 weeks. Word pairs were presented to groups of children who repeated the word items while either enacting the movements of the animal, running in place, or sitting at a desk. A cued-recall test administered following the final training session revealed that word recall was greater for children who were physically active during encoding than for children who were inactive. These findings were similar to those obtained in an experiment conducted with pre-school age children (van Dongen et al., 2016; Toumpaniari et al., 2015) and a series of experiments that focused on words acquired during geography, science, and mathematics instruction (Mavilidi et al., 2016, 2017, 2018). In several of these experiments, children’s long-term memory gain advantage was maintained for 6 weeks. In a recent meta-analysis affirming these findings, Schmid et al. (2023) report a large, positive relationship between physical activity and episodic free (Hedges g = 0.76) and cued (Hedges g = 0.84) recall memory. Similar to the present review, these results did not translate to recognition memory performance (Hedges g = 0.06).

One explanation advanced for children’s memory improvements in these experiments (Paas and Sweller, 2012) was based on Cognitive Load Theory, which makes specific hypotheses concerning the bidirectional relation between working memory and long-term memory stores. The theory posits that the limited operational capacity of working memory is offset by the availability of schemas stored in long-term memory. Schemas, which consist of multiple items, reduce the computational limitations of working memory. Paas and Sweller (2012) and Paas and Ayres (2014) draw on an evolutionary theory of human cognitive architecture (Geary, 2006), and suggest that schemas controlling motor movements take precedence over schemas that organize and refine the acquisition of semantic information. However, motor schemas can be used to leverage the encoding of secondary, academic material.

An alternative explanation for these findings (Mavilidi et al., 2021) is grounded in ecological theories of embodiment, which propose that learning emerges from a dynamical interaction among an individual’s body movements, the sensory experiences obtained from the movements, and the context of those movements (Lindgren and Johnson-Glenberg, 2013; Wade and Whiting, 2011; Newell, 1986). Memory of movements accumulates in real time via sensory and motor experiences obtained during physical actions that include gestures, walking, and play (Gallagher and Lindgren, 2015). Movements that occur during enactment are hypothesized to engage not only the motor system but also to facilitate the construction of mental representations that enhance memory recall (Cappuccio, 2019).

Several researchers have suggested that acute bouts of exercise may be particularly useful for enhancing cognition in developing children (Tomporowski et al., 2008; Howie and Pate, 2012; Donnelly et al., 2016). This conclusion should be taken with caution as our analyses were based on the results of a limited sample of experiments. If substantiated, the finding would be of importance to educators who could implicate exercise interventions in school setting to improve children's cognitive function.

3.5.1 Analyses of Moderators of Secondary Interest

The analyses revealed commonalities and differences with prior systematic reviews. Focusing on conditions in which exercise was performed prior to encoding, participants' age was found to influence long-term memory. Young adults had significantly better memory performance compared to older adults' performance. These results are in line with those of Roig et al. (2013) and Loprinzi et al. (2019a). The delay between encoding and subsequent tests of memory also influenced the strength of the relation. Performance on memory tests completed during the same day and within 24h later of encoding was significantly better when compared to longer delays, with the exception of one experiment that evidenced enhanced memory 2 weeks after encoding. Exercise intensity influenced memory performance at low and moderate levels, but not high intensity levels (Roig et al., 2013). These findings differ from those of Loprinzi et al. (2019a), who found high intensity exercise moderated long-term memory. Exercise mode also influenced memory performance, with aerobic exercise producing greater effects than anaerobic and resistance exercise. Exercise duration also impacted the relation, with medium to long durations producing greater effects than shorter durations. Cycling and running/walking impacted memory more than other activities (Loprinzi et al., 2019a).

Meta-analytic evidence supports the notion that chronic exercise interventions improve long-term memory (Northey et al., 2018) and executive function (Chen et al., 2020) among older adults. Additional evidence is needed to definitively clarify the relationship between acute exercise and long-term memory among older adults in clinical and applied settings. Children did not benefit from exercise under these encoding conditions. The delay between encoding and memory tests influenced the relation, with larger effects obtained when measured within 48h and 1 week following encoding than following shorter delays. It may be that the underlying brain structures involved in consolidation processes may lead to more durable episodic memory storage than the activation of prefrontal neural circuits produced by exercise performed prior to encoding. Exercise intensity performed at low- and moderate-levels resulted in larger positive effects than high intensity exercise, and exercise durations that were relatively long produced greater effects than shorter periods. Exercise type also moderated the relation, with anaerobic and resistance training producing greater effects than aerobic exercise. These results differ from those obtained under conditions in which exercise was performed prior to encoding. While these findings may reflect the limited number of effects available for analyses, they highlight an important variable in need of further examination. The role of exercise mode also differed for this analysis; cycling and other modes were superior to running/walking. The evidence for the moderating effects of specific variables on episodic memory obtained in this and prior reviews (Roig et al., 2013; Loprinzi et al., 2019a) provide numerous avenues for future research that explores the relation between exercise and cognition. The characteristics of the exercise modality impacted the relationship between exercise and long-term memory, regardless of the temporal relation. Given the range of exercise characteristics that were analyzed, the possibility of variability was highly likely, potentially impacting the interpretation of the results. The most common characteristics of exercise modalities in the present meta-analysis consisted of short, low to moderate intensity aerobic exercise protocols that were short in duration. The variation in exercise modalities often has been implicated as a potential mediator between the exercise-cognition relationship (Tomporowski and Pesce, 2019). Though the heterogeneity among exercise protocols may introduce some variability that makes interpretation of results difficult, it is evident that most randomized controlled trials utilize similar exercise protocols (*figure 3.4*).

3.5.2 Limitations and Future Directions

The primary finding of this review is that the strength of the exercise-memory relation depends on the type of memory process measured. It is acknowledged, however, that the results obtained were restricted to episodic long-term memory, which is only one of several types of memory processing. Additional research designed to understand how the interactions among multiple types of long-term memory processes (e.g., semantic, spatial, perceptual, and procedural) is needed. There are research areas that necessitate additional scrutiny. For example, the analysis of experiments in which participants exercised simultaneously while encoding yielded null effects. Yet, experiments conducted with children that involved multiple training sessions consistently reported memory gains for those who were physically active while encoding academic material. The duration of each lesson and the length of the instructional interventions were brief and it is unlikely that the physical activity induced the changes in brain structure and function found with chronic exercise interventions (McMorris, 2016b; Voss et al., 2011). In the main, researchers have made distinctions between acute, single-bout experiments and chronic exercise interventions lasting months. Chronic exercise experiments typically use pre- and post-treatment performance to assess the effects of the intervention. Relatively little is known about changes in the strength of memory traces that may occur over multiple training sessions. Few experiments that manipulate exercise provide information concerning the effects of repetition and practice on participant's long-term memory over repeated training sessions.

The selection of a single theory of long-term episodic memory (i.e., Atkinson and Shiffrin, 1968, 1971) to serve as a framework for the present review is a limitation. Episodic memory is a complex phenomenon that has attracted the attention of researchers for over 150 years. Numerous psychological theories have been proposed to explain the processes that underlie memory. Considerable theory-based research has been performed to address the variables that influence free-recall, cued-recall, and recognition memory (Piepmeier et al., 2020; Criss and Howard, 2015). The intent of the present review was not to test specific theories or models but, rather, to determine whether the effects of acute bouts of exercise have global or selective effects on episodic memory. The results of our review may stimulate additional research that derive hypotheses from psychological theories as well as from neurophysiological models proposed by Yonelinas et al. (2019) to explain how the context in which items are encoded influenced item storage, recall, and recognition.

Additional well-designed exercise experiments that explore conditions that promote memory encoding and retention are warranted. The assessment of the quality of the experiments selected for this review revealed that the majority were rated as poor or fair. The quality of such research can be bolstered by utilizing reporting guidelines as a method of best practice and by conducting experiments in which hypotheses are grounded in established psychological theory and confirmed by convergent evidence obtained from studies that explore the neurobiology of memory.

Our analyses for the effects of exercise prior to encoding revealed a significant regression intercept for the Egger's test, suggesting evidence of publication bias as a limitation. Effects of exercise after and during encoding did not reveal a significant regression intercept for the Egger's test. Future well-conducted experiments with limited publication bias are warranted to strengthen the current exercise-cognition literature.

Advances in exercise research that focus on moderators that influence the relation between exercise and long-term declarative memory will benefit academics who seek to explain the phenomenon as well as practitioners who plan interventions designed to influence cognitive functions. The results of our review are germane for translational research and application. Physical activity and exercise breaks during children's academic routines are often recommended as interventions that favorably impact class performance and learning (Tomporowski et al., 2015). The results of experiments that examine the effects of exercise on students' academic performance, however, are quite variable (see reviews by Donnelly et al., 2016; Daly-Smith et al., 2018; Singh et al., 2019). The discrepancies that exist across experiments that focus on academic progress may be explained, at least partially, by the temporal relation between physical activity and academic classwork and by the methods that are used to assess learning.

3.6 Conclusion

The present review and systematic meta-analysis focused on mental processes that underlie the encoding and retrieval of information from long-term episodic declarative memory as assessed by tests of free-recall, cued-recall, and recognition. Based on a contemporary theory of long-term memory, we provide evidence that bouts of exercise differentially influenced free-recall and recognition memory processes. Exercise performed prior to encoding influence memory search processes that are employed in free-recall memory tests but not cue-recall or recognition memory. Exercise may alter free-recall processes via mechanisms that impact working memory and attentional allocation policy. Exercise performed following encoding influence memory search processes that are employed during recognition memory and to a lesser degree cued-recall, but not free-recall. Exercise may alter the consolidation of episodic memory. These results provide a theory-based approach to predicting the effectiveness of exercise interventions designed to enhance memory storage and retrieval. Left to be disentangled are the research outcomes obtained from studies of episodic memory that examine the effects of exercise performed simultaneously with encoding. We obtained tantalizing evidence that young children may be impacted via properly designed dual-task academic interventions. Additional dual-task research may lead to the development of exercise interventions designed for children in academic settings as well as older adults who evidence degraded memory function.

3.6 Conflict of Interest

The authors declared that there is no potential conflict of interest.

References

Amico, G., & Schaefer, S. (2020). Running During Encoding Improves Word Learning for Children. *Frontiers in Psychology*, *11*, 684. https://doi.org/10.3389/fpsyg.2020.00684

Atkinson, R. C., & Shiffrin, R. M. (n.d.). Human Memory: A Proposed System and its Control Processes. *Human Memory*, 54.

Atkinson, R. C., & Shiffrin, R. M. (1971). The control of short-term memory. *Scientific American*, *225*(2), 82–90. https://doi.org/10.1038/scientificamerican0871-82

Austin, M., & Loprinzi, P. D. (2019). Acute exercise and mindfulness meditation on learning and memory: Randomized controlled intervention. *Health Promotion Perspectives*, *9*(4), 314–318. https://doi.org/10.15171/hpp.2019.43

Bowles, B., Crupi, C., Pigott, S., Parrent, A., Wiebe, S., Janzen, L., & Köhler, S. (2010). Double dissociation of selective recollection and familiarity impairments following two different surgical treatments for temporal-lobe epilepsy. *Neuropsychologia*, *48*(9), 2640–2647. https://doi.org/10.1016/j.neuropsychologia.2010.05.010

Brickman, A. M., Khan, U. A., Provenzano, F. A., Yeung, L.-K., Suzuki, W., Schroeter, H., Wall, M., Sloan, R. P., & Small, S. A. (2014). Enhancing dentate gyrus function with dietary flavanols improves cognition in older adults. *Nature Neuroscience*, *17*(12), 1798–1803. https://doi.org/10.1038/nn.3850

Cahill, L., & McGaugh, J. L. (1998). Mechanisms of emotional arousal and lasting declarative memory. *Trends in Neurosciences*, *21*(7), 294–299. https://doi.org/10.1016/s0166-2236(97)01214-9

Cappuccio, M. L. (2019). *Handbook of Embodied Cognition and Sport Psychology*. MIT Press.

Chang, Y. K., Labban, J. D., Gapin, J. I., & Etnier, J. L. (2012). The effects of acute exercise on cognitive performance: A meta-analysis. *Brain Research*, *1453*, 87–101. https://doi.org/10.1016/j.brainres.2012.02.068

Clarke, S. C., Cooper, N. R., Rana, M., & Mackintosh, B. (2018). Cognitive Interpretation Bias: The Effect of a Single Session Moderate Exercise Protocol on Anxiety and Depression. *Frontiers in Psychology*, *9*, 1363. https://doi.org/10.3389/fpsyg.2018.01363

Coles, K., & Tomporowski, P. D. (2008). Effects of acute exercise on executive processing, short-term and long-term memory. *Journal of Sports Sciences*, *26*(3), 333–344. https://doi.org/10.1080/02640410701591417

Cox, G. E., & Shiffrin, R. M. (2017). A dynamic approach to recognition memory. *Psychological Review*, *124*(6), 795–860. https://doi.org/10.1037/rev0000076

Craik, F. I. M., & Lockhart, R. S. (1972). Levels of processing: A framework for memory research. *Journal of Verbal Learning and Verbal Behavior*, *11*(6), 671–684. https://doi.org/10.1016/S0022-5371(72)80001-X

Criss, A. H. (2010). Differentiation and response bias in episodic memory: Evidence from reaction time distributions. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *36*(2), 484. https://doi.org/10.1037/a0018435

Criss, A. H., Aue, W. R., & Smith, L. (2011). The effects of word frequency and context variability in cued recall. *Journal of Memory and Language*, *64*, 119–132. https://doi.org/10.1016/j.jml.2010.10.001

Criss, A. H., & Howard, M. W. (2015). Models of episodic memory. In *The Oxford handbook of computational and mathematical psychology.* (pp. 165–183). Oxford University Press.

Criss, A. H., & Shiffrin, R. M. (20040712). Context Noise and Item Noise Jointly Determine Recognition Memory: A Comment on Dennis and Humphreys (2001). *Psychological Review*, *111*(3), 800. https://doi.org/10.1037/0033-295X.111.3.800

Daly-Smith, A. J., Zwolinsky, S., McKenna, J., Tomporowski, P. D., Defeyter, M. A., & Manley, A. (2018). Systematic review of acute physically active learning and classroom movement breaks on children’s physical activity, cognition, academic performance and classroom behaviour: Understanding critical design features. *BMJ Open Sport & Exercise Medicine*, *4*(1), e000341. https://doi.org/10.1136/bmjsem-2018-000341

Delancey, D., Frith, E., Sng, E., & Loprinzi, P. D. (2019). Randomized Controlled Trial Examining the Long-Term Memory Effects of Acute Exercise During the Memory Consolidation Stage of Memory Formation. *Journal of Cognitive Enhancement*, *3*(3), 245–250. https://doi.org/10.1007/s41465-018-0106-z

Dietrich, A., & Audiffren, M. (2011). The reticular-activating hypofrontality (RAH) model of acute exercise. *Neuroscience and Biobehavioral Reviews*, *35*(6), 1305–1325. https://doi.org/10.1016/j.neubiorev.2011.02.001

Dilley, E. K., Zou, L., & Loprinzi, P. D. (2019). The effects of acute exercise intensity on episodic and false memory among young adult college students. *Health Promotion Perspectives*, *9*(2), 143–149. https://doi.org/10.15171/hpp.2019.20

Donnelly, J. E., Hillman, C. H., Castelli, D., Etnier, J. L., Lee, S., Tomporowski, P., Lambourne, K., & Szabo-Reed, A. N. (2016). Physical Activity, Fitness, Cognitive Function, and Academic Achievement in Children: A Systematic Review. *Medicine and Science in Sports and Exercise*, *48*(6), 1197–1222. https://doi.org/10.1249/MSS.0000000000000901

Eichenbaum, H. (2017). Prefrontal-hippocampal interactions in episodic memory. *Nature Reviews. Neuroscience*, *18*(9), 547–558. https://doi.org/10.1038/nrn.2017.74

Eichenbaum, H., Yonelinas, A. P., & Ranganath, C. (2007). The medial temporal lobe and recognition memory. *Annual Review of Neuroscience*, *30*, 123–152. https://doi.org/10.1146/annurev.neuro.30.051606.094328

El-Sayes, J., Harasym, D., Turco, C. V., Locke, M. B., & Nelson, A. J. (2019). Exercise-Induced Neuroplasticity: A Mechanistic Model and Prospects for Promoting Plasticity. *The Neuroscientist: A Review Journal Bringing Neurobiology, Neurology and Psychiatry*, *25*(1), 65–85. https://doi.org/10.1177/1073858418771538

Etnier, J. L., Sprick, P. M., Labban, J. D., Shih, C.-H., Glass, S. M., & Vance, J. C. (2020). Effects of an aerobic fitness test on short- and long-term memory in elementary-aged children. *Journal of Sports Sciences*, *38*(19), 2264–2272. https://doi.org/10.1080/02640414.2020.1778251

Etnier, J. L., Vance, J. C., & Ueno, A. (2021a). Effects of acute exercise on memory performance in middle-aged and older adults. *Journal of Aging and Physical Activity*, *29*(5), 753–760. https://doi.org/10.1123/japa.2020-0208

Etnier, J. L., Vance, J. C., & Ueno, A. (2021b). Effects of Acute Exercise on Memory Performance in Middle-Aged and Older Adults. *Journal of Aging and Physical Activity*, *29*(5), 753–760. https://doi.org/10.1123/japa.2020-0208

Etnier, J., Labban, J. D., Piepmeier, A., Davis, M. E., & Henning, D. A. (2014). Effects of an acute bout of exercise on memory in 6th grade children. *Pediatric Exercise Science*, *26*(3), 250–258. https://doi.org/10.1123/pes.2013-0141

Frith, E., Sng, E., & Loprinzi, P. D. (2017). Randomized controlled trial evaluating the temporal effects of high-intensity exercise on learning, short-term and long-term memory, and prospective memory. *The European Journal of Neuroscience*, *46*(10), 2557–2564. https://doi.org/10.1111/ejn.13719

Gallagher, S., & Lindgren, R. (2015). Enactive Metaphors: Learning Through Full-Body Engagement. *Educational Psychology Review*, *27*(3), 391–404. https://doi.org/10.1007/s10648-015-9327-1

Garber, C. E., Blissmer, B., Deschenes, M. R., Franklin, B. A., Lamonte, M. J., Lee, I.-M., Nieman, D. C., Swain, D. P., & American College of Sports Medicine. (2011). American College of Sports Medicine position stand. Quantity and quality of exercise for developing and maintaining cardiorespiratory, musculoskeletal, and neuromotor fitness in apparently healthy adults: Guidance for prescribing exercise. *Medicine and Science in Sports and Exercise*, *43*(7), 1334–1359. https://doi.org/10.1249/MSS.0b013e318213fefb

Geary, D. C. (2006). Evolutionary developmental psychology: Current status and future directions. *Developmental Review*, *26*(2), 113–119. https://doi.org/10.1016/j.dr.2006.02.005

Gillund, G., & Shiffrin, R. M. (1984). A retrieval model for both recognition and recall. *Psychological Review*, *91*, 1–67. https://doi.org/10.1037/0033-295X.91.1.1

Gold, P. E., McIntyre, C., McNay, E., Stefani, M., & Korol, D. L. (2001). Neurochemical referees of dueling memory systems. In *Memory consolidation: Essays in honor of James L. McGaugh* (pp. 219–248). American Psychological Association. https://doi.org/10.1037/10413-012

Gomez-Pinilla, F., & Hillman, C. (2013). The influence of exercise on cognitive abilities. *Comprehensive Physiology*, *3*(1), 403–428. https://doi.org/10.1002/cphy.c110063

Green, D. M., & Swets, J. A. (1974). *Signal detection theory and psychophysics* (pp. xiii, 479). Robert E. Krieger.

Haynes, J. T., & Loprinzi, P. D. (2019). Acute Cardiovascular Exercise on Proactive Memory Interference. *Journal of Cognitive Enhancement*, *3*(2), 139–143. https://doi.org/10.1007/s41465-018-0101-4

Higgins, J. P. T., Thompson, S. G., Deeks, J. J., & Altman, D. G. (2003). Measuring inconsistency in meta-analyses. *BMJ (Clinical Research Ed.)*, *327*(7414), 557–560. https://doi.org/10.1136/bmj.327.7414.557

Hilgard, E. R. (1980). The trilogy of mind: Cognition, affection, and conation. *Journal of the History of the Behavioral Sciences*, *16*(2), 107–117. https://doi.org/10.1002/1520-6696(198004)16:2<107::AID-JHBS2300160202>3.0.CO;2-Y

Hillman, C. H., Erickson, K. I., & Kramer, A. F. (2008). Be smart, exercise your heart: Exercise effects on brain and cognition. *Nature Reviews. Neuroscience*, *9*(1), 58–65. https://doi.org/10.1038/nrn2298

Hockey, G. M., Gaillard, A. W. K., & Coles, M. (1986). *Energetics and Human Information Processing*. Springer Science & Business Media.

Howie, E. K., & Pate, R. R. (2012). Physical activity and academic achievement in children: A historical perspective. *Journal of Sport and Health Science*, *1*(3), 160–169. https://doi.org/10.1016/j.jshs.2012.09.003

Huedo-Medina, T. B., Sánchez-Meca, J., Marín-Martínez, F., & Botella, J. (2006). Assessing heterogeneity in meta-analysis: Q statistic or I^2 index? *Psychological Methods*, *11*(2), 193–206. https://doi.org/10.1037/1082-989X.11.2.193

Jentsch, V. L., & Wolf, O. T. (2020). Acute physical exercise promotes the consolidation of emotional material. *Neurobiology of Learning and Memory*, *173*, 107252. https://doi.org/10.1016/j.nlm.2020.107252

Johnson, L., Yao, J., Zou, L., Xiao, T., & Loprinzi, P. D. (2019). Mental Imagery and Acute Exercise on Episodic Memory Function. *Brain Sciences*, *9*(9), E237. https://doi.org/10.3390/brainsci9090237

Kahneman, D. (1973). *Attention and Effort*. Prentice-Hall.

Kao, S.-C., Drollette, E. S., Ritondale, J. P., Khan, N. A., & Hillman, C. H. (2018). The acute effects of high-intensity interval training and moderate-intensity continuous exercise on declarative memory and inhibitory control. *Psychology of Sport and Exercise*, *38*, 90–99.

Labban, J. D., & Etnier, J. L. (2011). Effects of acute exercise on long-term memory. *Research Quarterly for Exercise and Sport*, *82*(4), 712–721. https://doi.org/10.1080/02701367.2011.10599808

Labban, J. D., & Etnier, J. L. (2018). The Effect of Acute Exercise on Encoding and Consolidation of Long-Term Memory. *Journal of Sport and Exercise Psychology*, *40*(6), 336–342. https://doi.org/10.1123/jsep.2018-0072

Lambourne, K., & Tomporowski, P. (2010). The effect of exercise-induced arousal on cognitive task performance: A meta-regression analysis. *Brain Research*, *1341*, 12–24. https://doi.org/10.1016/j.brainres.2010.03.091

Lind, R. R., Beck, M. M., Wikman, J., Malarski, K., Krustrup, P., Lundbye-Jensen, J., & Geertsen, S. S. (2019). Acute high-intensity football games can improve children’s inhibitory control and neurophysiological measures of attention. *Scandinavian Journal of Medicine & Science in Sports*, *29*(10), 1546–1562. https://doi.org/10.1111/sms.13485

Lindgren, R., & Johnson-Glenberg, M. (2013). Emboldened by Embodiment: Six Precepts for Research on Embodied Learning and Mixed Reality. *Educational Researcher*, *42*(8), 445–452. https://doi.org/10.3102/0013189X13511661

Loprinzi, P. D. (2019). IGF-1 in exercise-induced enhancement of episodic memory. *Acta Physiologica (Oxford, England)*, *226*(1), e13154. https://doi.org/10.1111/apha.13154

Loprinzi, P. D., Blough, J., Crawford, L., Ryu, S., Zou, L., & Li, H. (2019). The Temporal Effects of Acute Exercise on Episodic Memory Function: Systematic Review with Meta-Analysis. *Brain Sciences*, *9*(4), E87. https://doi.org/10.3390/brainsci9040087

Loprinzi, P. D., Crawford, L., Moore, D., Blough, J., Burnett, G., Chism, M., & Robinson, G. (2021). Motor behavior-induced prefrontal cortex activation and episodic memory function. *International Journal of Neuroscience*, *132*, 133–153. https://doi.org/10.1080/00207454.2020.1803307

Loprinzi, P. D., Edwards, M. K., & Frith, E. (2017). Potential avenues for exercise to activate episodic memory-related pathways: A narrative review. *The European Journal of Neuroscience*, *46*(5), 2067–2077. https://doi.org/10.1111/ejn.13644

Loprinzi, P. D., Frith, E., & Crawford, L. (2020). The Effects of Acute Exercise on Retroactive Memory Interference. *American Journal of Health Promotion: AJHP*, *34*(1), 25–31. https://doi.org/10.1177/0890117119866138

Loprinzi, P. D., Green, D., Wages, S., Cheke, L. G., & Jones, T. (2020). Experimental Effects of Acute High-Intensity Resistance Exercise on Episodic Memory Function: Consideration for Post-Exercise Recovery Period. *Journal of Lifestyle Medicine*, *10*(1), 7–20. https://doi.org/10.15280/jlm.2020.10.1.7

Loprinzi, P. D., Harris, F., McRaney, K., Chism, M., Deming, R., Jones, T., Zou, L., & Tan, M. (2019). Effects of Acute Exercise and Learning Strategy Implementation on Memory Function. *Medicina*, *55*(9), 568. https://doi.org/10.3390/medicina55090568

Loprinzi, P. D., Koehler, L., Frith, E., Ponce, P., Delancey, D., Joyner, C., Ashpole, N. M., Zou, L., & Li, H. (2019). Acute Exercise, Psychological Stress Induction, and Episodic Memory. *American Journal of Health Behavior*, *43*(6), 1016–1029. https://doi.org/10.5993/AJHB.43.6.1

Ludyga, S., Gerber, M., Brand, S., Pühse, U., & Colledge, F. (2018). Effects of Aerobic Exercise on Cognitive Performance Among Young Adults in a Higher Education Setting. *Research Quarterly for Exercise and Sport*, *89*(2), 164–172. https://doi.org/10.1080/02701367.2018.1438575

Malmberg, K. J., Raaijmakers, J. G. W., & Shiffrin, R. M. (2019). 50 years of research sparked by Atkinson and Shiffrin (1968). *Memory & Cognition*, *47*(4), 561–574. https://doi.org/10.3758/s13421-019-00896-7

Mavilidi, M. F., Ouwehand, K., Schmidt, M., Pesce, C., Tomporowski, P. D., Okely, A. D., & Paas, F. (2021). *Embodiment as a pedagogical tool to enhance learning*. 26.

Mavilidi, M.-F., Okely, A., Chandler, P., Louise Domazet, S., & Paas, F. (2018). Immediate and delayed effects of integrating physical activity into preschool children's learning of numeracy skills. *Journal of Experimental Child Psychology*, *166*, 502–519. https://doi.org/10.1016/j.jecp.2017.09.009

Mavilidi, M.-F., Okely, A. D., Chandler, P., & Paas, F. (2016). Infusing Physical Activities Into the Classroom: Effects on Preschool Children's Geography Learning. *Mind, Brain, and Education*, *10*(4), 256–263. https://doi.org/10.1111/mbe.12131

Mavilidi, M.-F., Okely, A. D., Chandler, P., & Paas, F. (2017). Effects of Integrating Physical Activities Into a Science Lesson on Preschool Children's Learning and Enjoyment. *Applied Cognitive Psychology*, *31*(3), 281–290. https://doi.org/10.1002/acp.3325

McGaugh, J. L. (2000). Memory—A century of consolidation. *Science (New York, N.Y.)*, *287*(5451), 248–251. https://doi.org/10.1126/science.287.5451.248

McGaugh, J. L. (2004). The amygdala modulates the consolidation of memories of emotionally arousing experiences. *Annual Review of Neuroscience*, *27*, 1–28. https://doi.org/10.1146/annurev.neuro.27.070203.144157

McGaugh, J. L. (2015). Consolidating Memories. *Annual Review of Psychology*, *66*(1), 1–24. https://doi.org/10.1146/annurev-psych-010814-014954

McGaugh, J. L. (2018). Emotional arousal regulation of memory consolidation. *Current Opinion in Behavioral Sciences*, *19*, 55–60. https://doi.org/10.1016/j.cobeha.2017.10.003

McMorris, T. (2016a). Developing the catecholamines hypothesis for the acute exercise-cognition interaction in humans: Lessons from animal studies. *Physiology & Behavior*, *165*, 291–299. https://doi.org/10.1016/j.physbeh.2016.08.011

McMorris, T. (2016b). Reappraisal of the acute, moderate intensity exercise-catecholamines interaction effect on speed of cognition: Role of the vagal/NTS afferent pathway. *Journal of Applied Physiology (Bethesda, Md.: 1985)*, *120*(6), 657–658. https://doi.org/10.1152/japplphysiol.00749.2015

McMorris, T., & Hale, B. J. (2015). Is there an acute exercise-induced physiological/biochemical threshold which triggers increased speed of cognitive functioning? A meta-analytic investigation. *Journal of Sport and Health Science*, *4*(1), 4–13. https://doi.org/10.1016/j.jshs.2014.08.003

McMorris, T., Hale, B. J., Corbett, J., Robertson, K., & Hodgson, C. I. (2015). Does acute exercise affect the performance of whole-body, psychomotor skills in an inverted-U fashion? A meta-analytic investigation. *Physiology & Behavior*, *141*, 180–189. https://doi.org/10.1016/j.physbeh.2015.01.010

McMorris, T., Tomporowski, P. D., & Audiffren, M. (Eds.). (2009). *Exercise and cognitive function*. Wiley.

McNerney, M. W., & Radvansky, G. A. (2015). Mind racing: The influence of exercise on long-term memory consolidation. *Memory (Hove, England)*, *23*(8), 1140–1151. https://doi.org/10.1080/09658211.2014.962545

McSween, M.-P., McMahon, K. L., Maguire, K., Coombes, J. S., Rodriguez, A. D., Erickson, K. I., & Copland, D. A. (2021). The Acute Effects of Different Exercise Intensities on Associative Novel Word Learning in Healthy Older Adults: A Randomized Controlled Trial. *Journal of Aging and Physical Activity*, *29*(5), 793–806. https://doi.org/10.1123/japa.2020-0093

Meeusen, R., Schaefer, S., Tomporowski, P., & Bailey, R. (2017). *Physical Activity and Educational Achievement: Insights from Exercise Neuroscience*. Routledge.

Most, S. B., Kennedy, B. L., & Petras, E. A. (2017). Evidence for improved memory from 5 minutes of immediate, post-encoding exercise among women. *Cognitive Research: Principles and Implications*, *2*(1), 33. https://doi.org/10.1186/s41235-017-0068-1

Newell, K. M. (1986). Constraints on the Development of Coordination. In M. G. Wade & H. T. A. Whiting (Eds.), *Motor Development in Children: Aspects of Coordination and Control* (pp. 341–360). Springer Netherlands. https://doi.org/10.1007/978-94-009-4460-2_19

O'Connor, S. R., Tully, M. A., Ryan, B., Bradley, J. M., Baxter, G. D., & McDonough, S. M. (2015). Failure of a numerical quality assessment scale to identify potential risk of bias in a systematic review: A comparison study. *BMC Research Notes*, *8*, 224. https://doi.org/10.1186/s13104-015-1181-1

Paas, F., & Ayres, P. (2014). Cognitive Load Theory: A Broader View on the Role of Memory in Learning and Education. *Educational Psychology Review*, *26*(2), 191–195. https://doi.org/10.1007/s10648-014-9263-5

Paas, F., & Sweller, J. (2012). An Evolutionary Upgrade of Cognitive Load Theory: Using the Human Motor System and Collaboration to Support the Learning of Complex Cognitive Tasks. *Educational Psychology Review*, *24*(1), 27–45. https://doi.org/10.1007/s10648-011-9179-2

Palmer, M. A., Stefanidis, K., Turner, A., Tranent, P. J., Breen, R., Kucina, T., Brumby, L., Holt, G. A., Fell, J. W., & Sauer, J. D. (2019). Acute Physical Exercise Can Influence the Accuracy of Metacognitive Judgments. *Scientific Reports*, *9*, 12412. https://doi.org/10.1038/s41598-019-48861-3

Pesce, C., Crova, C., Cereatti, L., Casella, R., & Bellucci, M. (2009). Physical activity and mental performance in preadolescents: Effects of acute exercise on free-recall memory. *Mental Health and Physical Activity*, *2*, 16–22. https://doi.org/10.1016/j.mhpa.2009.02.001

Piepmeier, A. T., Etnier, J. L., Wideman, L., Berry, N. T., Kincaid, Z., & Weaver, M. A. (2020). A preliminary investigation of acute exercise intensity on memory and BDNF isoform concentrations. *European Journal of Sport Science*, *20*(6), 819–830. https://doi.org/10.1080/17461391.2019.1660726

Plummer, P., Eskes, G., Wallace, S., Giuffrida, C., Fraas, M., Campbell, G., Clifton, K.-L., Skidmore, E. R., & American Congress of Rehabilitation Medicine Stroke Networking Group Cognition Task Force. (2013). Cognitive-motor interference during functional mobility after stroke: State of the science and implications for future research. *Archives of Physical Medicine and Rehabilitation*, *94*(12), 2565-2574.e6. https://doi.org/10.1016/j.apmr.2013.08.002

Pyke, W., Ifram, F., Coventry, L., Sung, Y., Champion, I., & Javadi, A.-H. (2020). The effects of different protocols of physical exercise and rest on long-term memory. *Neurobiology of Learning and Memory*, *167*, 107128. https://doi.org/10.1016/j.nlm.2019.107128

Raaijmakers, J. G., & Shiffrin, R. M. (1981). Search of associative memory. *Psychological Review*, *88*, 93–134. https://doi.org/10.1037/0033-295X.88.2.93

Roig, M., Nordbrandt, S., Geertsen, S. S., & Nielsen, J. B. (2013). The effects of cardiovascular exercise on human memory: A review with meta-analysis. *Neuroscience and Biobehavioral Reviews*, *37*(8), 1645–1666. https://doi.org/10.1016/j.neubiorev.2013.06.012

Salas, C. R., Minakata, K., & Kelemen, W. L. (2011). Walking before study enhances free recall but not judgement-of-learning magnitude. *Journal of Cognitive Psychology*, *23*(4), 507–513. https://doi.org/10.1080/20445911.2011.532207

Schacter, D. L., Curran, T., Reiman, E. M., Chen, K., Bandy, D. J., & Frost, J. T. (1999). Medial temporal lobe activation during episodic encoding and retrieval: A PET study. *Hippocampus*, *9*(5), 575–581. https://doi.org/10.1002/(SICI)1098-1063(1999)9:5<575::AID-HIPO11>3.0.CO;2-K

Schmid, D. G., Scott, N. M., & Tomporowski, P. D. (2023). Physical Activity and Children's Episodic Memory: A Meta-Analysis. *Pediatric Exercise Science*, 1–15. https://doi.org/10.1123/pes.2023-0020

Schmidt, M., Benzing, V., Wallman-Jones, A., Mavilidi, M.-F., Lubans, D. R., & Paas, F. (2019). Embodied learning in the classroom: Effects on primary school children's attention and foreign language vocabulary learning. *Psychology of Sport and Exercise*, *43*, 45–54. https://doi.org/10.1016/j.psychsport.2018.12.017

Schmidt-Kassow, M., Deusser, M., Thiel, C., Otterbein, S., Montag, C., Reuter, M., Banzer, W., & Kaiser, J. (2013). Physical Exercise during Encoding Improves Vocabulary Learning in Young Female Adults: A Neuroendocrinological Study. *PLOS ONE*, *8*(5), e64172. https://doi.org/10.1371/journal.pone.0064172

Schmidt-Kassow, M., Kulka, A., Gunter, T. C., Rothermich, K., & Kotz, S. A. (2010). Exercising during learning improves vocabulary acquisition: Behavioral and ERP evidence. *Neuroscience Letters*, *482*(1), 40–44. https://doi.org/10.1016/j.neulet.2010.06.089

Schmidt-Kassow, M., Zink, N., Mock, J., Thiel, C., Vogt, L., Abel, C., & Kaiser, J. (2014). Treadmill walking during vocabulary encoding improves verbal long-term memory. *Behavioral and Brain Functions*, *10*(1), 24. https://doi.org/10.1186/1744-9081-10-24

Schramke, C. J., & Bauer, R. M. (1997). State-dependent learning in older and younger adults. *Psychology and Aging*, *12*, 255–262. https://doi.org/10.1037/0882-7974.12.2.255

Segal, S. K., Cotman, C. W., & Cahill, L. F. (2012). Exercise-Induced Noradrenergic Activation Enhances Memory Consolidation in Both Normal Aging and Patients with Amnestic Mild Cognitive Impairment. *Journal of Alzheimer's Disease*, *32*(4), 1011–1018. https://doi.org/10.3233/JAD-2012-121078

Shiffrin, R. M., & Steyvers, M. (1997). A model for recognition memory: REM—retrieving effectively from memory. *Psychonomic Bulletin & Review*, *4*, 145–166. https://doi.org/10.3758/BF03209391

Siddaway, A. P., Wood, A. M., & Hedges, L. V. (2019). How to Do a Systematic Review: A Best Practice Guide for Conducting and Reporting Narrative Reviews, Meta-Analyses, and Meta-Syntheses. *Annual Review of Psychology*, *70*, 747–770. https://doi.org/10.1146/annurev-psych-010418-102803

Siddiqui, A., & Loprinzi, P. D. (2018). Experimental Investigation of the Time Course Effects of Acute Exercise on False Episodic Memory. *Journal of Clinical Medicine*, *7*(7), E157. https://doi.org/10.3390/jcm7070157

Singh, A. S., Saliasi, E., van den Berg, V., Uijtdewilligen, L., de Groot, R. H. M., Jolles, J., Andersen, L. B., Bailey, R., Chang, Y.-K., Diamond, A., Ericsson, I., Etnier, J. L., Fedewa, A. L., Hillman, C. H., McMorris, T., Pesce, C., Pühse, U., Tomporowski, P. D., & Chinapaw, M. J. M. (2019). Effects of physical activity interventions on cognitive and academic performance in children and adolescents: A novel combination of a systematic review and recommendations from an expert panel. *British Journal of Sports Medicine*, *53*(10), 640–647. https://doi.org/10.1136/bjsports-2017-098136

Slutsky-Ganesh, A. B., Etnier, J. L., & Labban, J. D. (2020). Acute exercise, memory, and neural activation in young adults. *International Journal of Psychophysiology: Official Journal of the International Organization of Psychophysiology*, *158*, 299–309. https://doi.org/10.1016/j.ijpsycho.2020.09.018

Sng, E., Frith, E., & Loprinzi, P. D. (2018). Temporal Effects of Acute Walking Exercise on Learning and Memory Function. *American Journal of Health Promotion: AJHP*, *32*(7), 1518–1525. https://doi.org/10.1177/0890117117749476

Soga, K., Kamijo, K., & Masaki, H. (2017). Aerobic Exercise During Encoding Impairs Hippocampus-Dependent Memory. *Journal of Sport & Exercise Psychology*, *39*(4), 249–260. https://doi.org/10.1123/jsep.2016-0254

Spirduso, W. W., Poon, L. W., & Chodzko-Zajko, W. J. (2007). *Exercise and Its Mediating Effects on Cognition*. Human Kinetics.

Squire, L. R., & Wixted, J. T. (2011). The cognitive neuroscience of human memory since H.M. *Annual Review of Neuroscience*, *34*, 259–288. https://doi.org/10.1146/annurev-neuro-061010-113720

Stanislaw, H., & Todorov, N. (1999). Calculation of signal detection theory measures. *Behavior Research Methods, Instruments & Computers*, *31*, 137–149. https://doi.org/10.3758/BF03207704

Stones, M. J., & Dawe, D. (1993). Acute exercise facilitates semantically cued memory in nursing home residents. *Journal of the American Geriatrics Society*, *41*, 531–534. https://doi.org/10.1111/j.1532-5415.1993.tb01890.x

Tomporowski, P. D. (2003). Effects of acute bouts of exercise on cognition. *Acta Psychologica*, *112*(3), 297–324. https://doi.org/10.1016/s0001-6918(02)00134-8

Tomporowski, P. D., Davis, C. L., Miller, P. H., & Naglieri, J. A. (2008). Exercise and Children's Intelligence, Cognition, and Academic Achievement. *Educational Psychology Review*, *20*(2), 111–131. https://doi.org/10.1007/s10648-007-9057-0

Tomporowski, P. D., & Qazi, A. S. (2020). Cognitive-Motor Dual Task Interference Effects on Declarative Memory: A Theory-Based Review. *Frontiers in Psychology*, *11*, 1015. https://doi.org/10.3389/fpsyg.2020.01015

Tomporowski, P., McCullick, B. A., & Pesce, C. (2015). *Enhancing Children's Cognition With Physical Activity Games*. Human Kinetics.

Toumpaniari, K., Loyens, S., Mavilidi, M.-F., & Paas, F. (2015). Preschool children's foreign language vocabulary learning by embodying words through physical activity and gesturing. *Educational Psychology Review*, *27*, 445–456. https://doi.org/10.1007/s10648-015-9316-4

van Dongen, E. V., Kersten, I. H. P., Wagner, I. C., Morris, R. G. M., & Fernández, G. (2016). Physical Exercise Performed Four Hours after Learning Improves Memory Retention and Increases Hippocampal Pattern Similarity during Retrieval. *Current Biology: CB*, *26*(13), 1722–1727. https://doi.org/10.1016/j.cub.2016.04.071

Voss, M. W., Nagamatsu, L. S., Liu-Ambrose, T., & Kramer, A. F. (2011). Exercise, brain, and cognition across the life span. *Journal of Applied Physiology (Bethesda, Md.: 1985)*, *111*(5), 1505–1513. https://doi.org/10.1152/japplphysiol.00210.2011

Wade, B., & Loprinzi, P. D. (2018). The Experimental Effects of Acute Exercise on Long-Term Emotional Memory. *Journal of Clinical Medicine*, *7*(12), E486. https://doi.org/10.3390/jcm7120486

Wade, M. G., & Whiting, H. T. A. (2011). *Motor Development in Children: Aspects of Coordination and Control*. Springer Netherlands.

Wang, X., Zhu, R., Zhou, C., & Chen, Y. (2020). Distinct Effects of Acute Aerobic Exercise on Declarative Memory and Procedural Memory Formation. *Brain Sciences*, *10*(10), 691. https://doi.org/10.3390/brainsci10100691

Wanner, P., Cheng, F.-H., & Steib, S. (2020). Effects of acute cardiovascular exercise on motor memory encoding and consolidation: A systematic review with meta-analysis. *Neuroscience and Biobehavioral Reviews*, *116*, 365–381. https://doi.org/10.1016/j.neubiorev.2020.06.018

Warm, J. S. (Ed.). (1984). *Sustained Attention in Human Performance* (1st edition). Wiley.

Weinberg, L., Hasni, A., Shinohara, M., & Duarte, A. (2014). A single bout of resistance exercise can enhance episodic memory performance. *Acta Psychologica*, *153*, 13–19. https://doi.org/10.1016/j.actpsy.2014.06.011

Wickens, C. D. (2008). Multiple resources and mental workload. *Human Factors*, *50*(3), 449–455. https://doi.org/10.1518/001872008X288394

Wilson, J. H., & Criss, A. H. (2017). The list strength effect in cued recall. *Journal of Memory and Language*, *95*, 78–88. https://doi.org/10.1016/j.jml.2017.01.006

Winter, B., Breitenstein, C., Mooren, F. C., Voelker, K., Fobker, M., Lechtermann, A., Krueger, K., Fromme, A., Korsukewitz, C., Floel, A., & Knecht, S. (2007). High impact running improves learning. *Neurobiology of Learning and Memory*, *87*(4), 597–609. https://doi.org/10.1016/j.nlm.2006.11.003

Winters, B. D., Forwood, S. E., Cowell, R. A., Saksida, L. M., & Bussey, T. J. (2004). Double Dissociation between the Effects of Peri-Postrhinal Cortex and Hippocampal Lesions on Tests of Object Recognition and Spatial Memory: Heterogeneity of Function within the Temporal Lobe. *Journal of Neuroscience*, *24*(26), 5901–5908. https://doi.org/10.1523/JNEUROSCI.1346-04.2004

Yanes, D., Frith, E., & Loprinzi, P. D. (2019). Memory-Related Encoding-Specificity Paradigm: Experimental Application to the Exercise Domain. *Europe's Journal of Psychology*, *15*(3), Article 3. https://doi.org/10.5964/ejop.v15i3.1767

Yanes, D., & Loprinzi, P. D. (2018). Experimental Effects of Acute Exercise on Iconic Memory, Short-Term Episodic, and Long-Term Episodic Memory. *Journal of Clinical Medicine*, *7*(6), 146. https://doi.org/10.3390/jcm7060146

Yerkes, R. M., & Dodson, J. D. (1908). The relation of strength of stimulus to rapidity of habit-formation. *Journal of Comparative Neurology and Psychology*, *18*(5), 459–482. https://doi.org/10.1002/cne.920180503

Yonelinas, A. P., Ranganath, C., Ekstrom, A. D., & Wiltgen, B. J. (2019). A contextual binding theory of episodic memory: Systems consolidation reconsidered. *Nature Reviews Neuroscience*, *20*(6), Article 6. https://doi.org/10.1038/s41583-019-0150-4

Zabriskie, H. A., & Heath, E. M. (2019). Effectiveness of Studying When Coupled with Exercise-Induced Arousal. *International Journal of Exercise Science*, *12*(5), 979–988.

Zuniga, K. E., Mueller, M., Santana, A. R., & Kelemen, W. L. (2019). Acute aerobic exercise improves memory across intensity and fitness levels. *Memory (Hove, England)*, *27*(5), 628–636. https://doi.org/10.1080/09658211.2018.1546875

CHAPTER 4

THE EFFECTS OF AN ACUTE BOUT OF PHYSICAL ACTIVITY ON YOUNG ADULTS' ATTENTION, EPISODIC, AND OBJECT-LOCATION MEMORY[2]

---

[2] Qazi, A.S. & Tomporowski, P.D. To be submitted to *International Journal of Sport and Exercise Psychology*.

Abstract

Previous research indicated that acute physical activity facilitates long-term memory. The mechanisms by which the type and timing of physical activity influence memory encoding remain unclear. The purpose of the present study was to evaluate the effects of two types of physical activity which differ in complexity on free-recall, recognition, and object location memory. A between-group design was employed in which participants (n = 60, age 20.25 ∓ 1.73 years, 66 % F) were assigned via a blocked randomization method to one of 3 conditions: complex motor training, simple motor training, or control. Participants engaged in a 15-minute physical activity protocol or seated rest. The Digit Cancellation Task of attention was then administered. After the digit cancellation task, participants completed a visuospatial memory task in which free-recall, recognition, and object location memory retention tests were administered immediately, 24-hours, and 7-days after physical activity or rest to assess long-term memory. The intensity of the physical activity was measured using the Borg's Rating of Perceived Exertion scale and heart rate. The effects of physical activity on free-recall, recognition, and object location memory were assessed via a 3(Group) X 3(Time) mixed-factorial ANOVA. Analyses of free-recall revealed a main effect for Group, F(2, 57) = 8.785, $p < 0.05$, $\eta_p^2 = 0.236$, and Time, F(1.82, 57) = 6.645, $p < 0.05$, $\eta_p^2 = 0.104$. The Group X Time interaction was non-significant, F(3.63, 103.43) = 1.642, $\eta_p^2 = 0.54$. An additional 3(group) x 2(time) analysis of late retention intervals revealed a significant Group X Time interaction, F(2, 57) = 3.171, $p < 0.05$, $\eta p2 = 0.10$. Analyses of recognition data revealed a main effect for Time, F(1.68, 57) = 99.972, $p < 0.05$, $\eta_p^2 = 0.637$, but no significant main effect for Group, F(2, 57) =

1.282, $p = 0.285$, $\eta_p^2 = 0.043$, nor Group X Time interaction, F(3.36, 95.68) = 0.256, $p = 0.905$, $\eta_p^2 = 0.01$. Analyses of object location memory data revealed a main effect for Time, F(1.56, 57) = 139.090, $p < 0.05$, $\eta_p^2 = 0.709$, and no significant main effect for Group, F(2, 57) = 2.588, p = 0.084, $\eta_p^2 = 0.083$, nor Group X Time interaction, F(3.12, 114) = 0.690, $p = 0.566$, $\eta_p^2 = 0.024$. RPE and HR measures did not differ between groups. Participants who completed a complex bout of physical activity demonstrated greater and more durable free-recall memory, but not recognition nor object location memory compared to those who completed the simple physical activity and or control condition. The differential impact of physical activity on long-term memory depended on the type of physical activity that was performed regarding its mental engagement. These results are in line with meta-analytical evidence that physical activity performed prior to encoding impacts free-recall memory more than other memory process. These findings may be elucidated by theory-based explanations regarding the storage and retrieval of memory.

Keywords: physical activity, attention, long-term memory, short-term memory, encoding

4.2 Introduction

Both acute and chronic physical activity have been proposed and shown to be a crucial process for the preservation and/or enhancement of cognitive function among a variety of populations, including children (Chaddock-Heyman et al., 2014; de Greeff et al., 2018a; Khan & Hillman, 2014; Ludyga et al., 2016), adolescents (Esteban-Cornejo et al., 2015; Li et al., 2017), adults (Cox et al., 2016; Verburgh et al., 2014), and older adults (Chen et al., 2020; Etnier et al., 2019; Northey et al., 2018). The relationship between physical activity and cognition has been studied extensively for last several decades, establishing a clear link between the two. These effects of physical activity on cognition have important implications for the developing and aging brain.

Cognition is defined as an umbrella term that encompasses a wide range of mental abilities necessary to perceive, process, and interact with the environment. Human cognition has been studied via biological, neurophysiological, psychological, and theoretical perspectives and provide convergent explanation for its function. Despite the accumulating evidence, the specific mechanisms underlying the physical activity-cognition relationship are unclear. Numerous reviews have led to experiments that have explored the precise effects that physical activity has on specific components of cognition, including attention and long-term memory.

From an evolutionary neuroscientific perspective, physical activity has been linked to multiple components of cognition (Raichlen & Alexander, 2017). Over the course of two million years, there was a transition to cognitively engaging movement patterns that were necessary for survival. These movement patterns included components of motor control, short- and long-term memory, spatial memory, and later, executive function. According to the Adaptive Capacity Model, neural adaptations result in enhanced biological responses to physical activity. This is an especially important component for the cognitive improvement across the lifespan (Raichlen & Alexander, 2017). The Adaptive Capacity Model further suggests that the combination of physical activity and cognitive engagement acts to preserve and enhance neural resources. Cognitively engaging physical activity combines aerobic activity with motor control systems that rely on the spatial navigation, memory, attention, and components of executive function. When cognitive components are linked with physical activity, selective neuroplastic effects may result. The Adaptive Capacity Model predicts that physical activity interventions that do not include complex cognitive processing do not maximize the effects of physical activity on the brain (Raichlen & Alexander, 2017).

Experiments conducted with animal models provide evidence that physical activity enhances memory via several mechanisms. The impact of physical activity on memory has been explained via mechanisms including synaptic plasticity (Shih et al., 2013), increases in neuronal density (Uysal et al., 2005), hippocampal neurogenesis (Gomes da Silva et al., 2012), enhanced expressions of brain-derived neurotrophic factor levels (Hopkins et al., 2011), and other molecular mechanisms (Cassilhas et al., 2012). In regard to cognitively engaging physical activity, several experiments have shown that a cognitively enriched environment produces gains in different memory components via elevated hippocampal function in mice (Bechara & Kelly, 2013; Kobilo et al., 2011). Cognitively engaging, or complex bouts of physical activity have been shown to have a greater effect on the human brain than non-engaging, or simple physical activity alone. The timing of the physical activity bout in relation to the cognitive task is also important to consider.

A growing body of literature has also assessed the specific components of memory processes. Episodic memory represents the conscious recollection of previous experiences that are associated with the context in which the memory was initially experienced (Tulving, 2002). Episodic memory is typically measured via tests of free-recall, recognition, and spatial location. Free-recall memory is characterized by an individual’s ability to remember items without the aid of cues (Malmberg et al., 2019). Recognition memory is characterized by the ability to identify whether or not a specific item (e.g., word) was previously seen or not. Spatial memory is a distinct short- and long-term memory process that refers to the ability to encode and recall information about configurations, locations, or routes (Kessels et al., 2001). Spatial memory processes function collectively with other biological systems to allow for the operation of normal day-to-day functions. For example, object-location memory is a component of spatial memory that enables individuals to remember to locations of objects and navigate about their environment (Kessels et al., 2001).

Animal models have provided strong evidence that cognitive challenges and physical activity stimulate specific beneficial effects in the brain. These findings have also been translated to human models. Early research provided initial evidence that spatial memory for location develops very early in life and remains stable across age. Assessments of free-recall, recognition, and object-location memory were employed in a series of experiments (Dulaney & Ellis, 1991; Ellis et al., 1989; Katz & Ellis, 1991) that evaluated individuals who differed in age and intelligence levels. In these experiments, object location and recall memory were assessed. The overall results of the experiments indicated that memory of object location was invariant across age groups as well as intelligence levels. There were however IQ differences in free-recall memory in favor of free-recall processing. The researchers concluded that processes underlying spatial memory develop early in life and remain stable throughout.

The impact of physical activity on free-recall, recognition, and object-location memory was explored in the present experiment. In addition, the role of attentional processes during encoding was assessed. The construct of attention is proposed to directly facilitate memory encoding process (Chun & Turk-Browne, 2007). However, the exact details of the relationship are poorly understood. Attention is often viewed as the ‘gateway’ to the successful encoding of information. However, prior experiments have not directly examined whether or not attention mediates the relationship between physical activity and long-term memory. Methods employed in dual-task research provides the means to evaluate the relation between attention, encoding, and storage of memory. Dual-tasking refers to the simultaneous performance of a motor-motor or motor-cognitive task that is assessed independently (Leland et al., 2017). In these conditions, a primary and a secondary task require the allocation of attentional resources. Due to a limited pool of attentional of resources that are present at a given time, there is competition during dual-tasking as to which task will require the most resources (Kahneman, 1973). Researchers have hypothesized that attending to specific pieces of information will increase the likelihood of their successful consolidation into long-term memory.

Building upon theories of attention and long-term memory, the present experiment was designed to evaluate the effects of acute physical activity on young adults’ long-term episodic memory. The first aim of the experiment was to determine if long-term free-recall episodic memory and object-location memory are influenced by an acute bout of physical activity that occurs prior to learning. A single bout of physical activity prior to encoding among young adults was hypothesized to produce better free-recall, recognition, and object-location memory compared to young adults who did not perform any physical activity. The second aim of the experiment was to determine the effect of physical activity complexity on long-term free-recall, recognition, and object location memory. Participants who completed the complex physical activity bout were hypothesized to display better learning and improved free-recall, recognition, and object-location memory performance compared to the simple physical activity and control conditions. The third aim of the present experiment was to determine the role of attentional processes as a mediator of the relationship between physical activity and long-term free-recall memory. Attentional processes were hypothesized to significantly mediate the relationship between physical activity and long-term memory.

4.3 Methods

The following research protocol was approved by the University of Georgia Institutional Review Board and was in line with the APA guidelines for ethical research practices.

Participants

Participants were recruited via informational flyers posted on bulletin boards and other locations throughout the UGA campus, emails circulated via departmental listservs, postings on UGA's online learning management system (eLC), in-class recruitment, and word of mouth. Recruitment materials summarized the experiment, provided the exclusion criteria, and directed potential participants to the screening questionnaire on Qualtrics. The screening questionnaire determined if potential participants met all exclusion/inclusion criteria. Participants were screened to determine eligibility to partake in the experiment. Specifically, all participants that took part in the experiment were between the ages of 18-30 years. Anyone that indicated contraindications to maximal aerobic training based on the American College of Sports Medicine guidelines (i.e., cardiovascular complications, neuromuscular, musculoskeletal, or rheumatoid disorders), use of psychoactive medication (i.e., antidepressants, CNS stimulants), movement disorders, or diagnoses of sensory or learning disorders (i.e., attention deficit hyperactivity disorder) was excluded from participation in the study. Participants were also excluded if they did not consider English as their first language. Seventy-seven potential participants completed the screening questionnaire. Of the 77, the first 60 participants were scheduled for data collection visits. Fifty-nine participants completed all study procedures. One participant dropped out prior to completion due to a scheduling conflict. The final analysis included 59 participants. All participants that completed the study were compensated for their time with extra credit for eligible courses and $20 provided in the form of cash.

Participants were assigned via a blocked randomization method to one of 3 conditions: complex motor training, simple motor training, or control. A blocked randomization procedure via the website was utilized to randomly and evenly allocate participants to each group. Participants in each group completed either an PA or control protocol prior to the test of attention and memory encoding phase of the experiment. The complex motor training group completed a complex PA sequence, the simple motor training group completed a simple PA sequence, and the control group did not partake in any PA. The PA and control protocols were equal in duration. Both the complex and simple conditions elicited similar physiological arousal as indicated by heartrate and RPE values to ensure that the dose of PA was consistent across these exercise conditions.

Study design

This experiment utilized a mixed-factor design employing a between-subjects factor (Condition: complex physical activity, simple physical activity, or control) and a within-subjects factor (Time: immediate, 24-hr., 7-day). The primary dependent variable was episodic memory measured by free-recall, recognition, and object location memory. The independent variable was condition; complex physical activity, simple physical activity, or control. The intervening, or mediating variable, was attention.

Sample Size and Statistical Power

A meta-analysis on the effects of cardiovascular exercise on human memory revealed that acute exercise had a moderate effect (d = 0.26) on long-term memory (Roig et al., 2013a). Another meta-analysis indicated that acute exercise occurring before memory encoding resulted in a small effect (d = 0.11) (Loprinzi et al., 2019). A more recent meta-analysis further explored the effects of acute bouts of exercise before, during, or after encoding on free-, cued-recall, and recognition long-term memory. Results revealed that exercise before encoding improved memory with the largest effect on free-recall memory (*d* = 0.40) (Qazi et al., 2024). Based on these data and in accordance with the a priori hypotheses, an effect of 0.35 was used to determine the target sample size for the current experiment. Using the G*Power software program (http://www.gpower.hhu.de/), a total sample size of 57 participants indicated an effect of 0.35 at a 0.80 power level, with an alpha level α set to 0.05 (Faul et al., 2009). Assuming exclusions and dropouts, the target recruitment goal for the experiment was set at 60 participants, amounting to 20 participants to each of the three conditions. This sample size is in line with the literature which typically indicates a median sample size of 20 participants within each treatment arm of an experiment (Pontifex et al., 2019).

Procedure

Participants were required to report to the Cognition and Skill Acquisition Laboratory at approximately the same time of day (± 1 hour) on three separate occasions. The first and second testing sessions were separated by approximately 24 hours, and the second and third testing sessions were separated by approximately 6 days. These timepoints provided an assessment of memory immediately after encoding (session 1), 24 hours after encoding (session 2), and 7 days after encoding (session 3). Similar timepoints have been used previously by others (Loprinzi et al). During session 1, participants were provided an overview of the study by the research personnel. Participants also completed the informed consent, Godin leisure-time exercise questionnaire (Godin & Shephard, 1985), a modified version of the intrinsic motivation inventory (McAuley et al., 1989; Ryan, 1982), a self-administered medical history questionnaire, and a 24-hour history questionnaire to determine sleep patterns, caffeine intake, and general mood. Attempts to keep these factors stable across all testing sessions were made. Participants were told verbally to keep sleep patterns and caffeine intake stable prior to and during testing days. Participants were then asked during all follow-up testing sessions if these factors were kept consistent. Follow-up sessions were rescheduled if participant reported more or less than 2 hours of sleep within their normal range, if participant reported a major life event within the past 24 hours, or if participant reported elevated alcohol consumption within the past 24 hours (greater than 10 units of alcohol for men, greater than 7 units of alcohol for women) (Acheson et al., 1998). The 24-hour history questionnaire was completed prior to each testing session to assess consistency across all sessions. Height and weight measurements were then collected. After completing all preliminary paperwork and anthropometric measurements, the research investigator provided detailed instructions regarding the upcoming testing procedures. The participant was educated on donning a heart rate monitor and was then fitted with the same chest-mounted heart rate monitor (Polar, Model 0537). A resting heartrate was established following a 3-minute seated rest period during which the participant was asked to maintain a normal breathing pattern and to refrain from using his/her cellphones or any other electronic devices. Next, the participant was provided with a standardized explanation of the rating of perceived exertion (RPE) via prerecorded audio scripts (Borg, 1998). Next, participant was instructed to complete a 3-minute warmup on a motorized treadmill at a self-selected pace. Immediately after the conclusion of the warmup, heartrate and RPE measures were collected. Upon completion of the warmup, the participant was escorted to the testing area and was instructed to stand at a predetermined location on the floor indicated by a blue mark. The participant was then provided with standardized instructions for the PA protocol to follow via standardized prerecorded audio scripts. Any questions regarding the PA protocol were answered at this time.

Physical activity intervention

Two versions of the Quadrato Motor Training (QMT) physical activity intervention, simple and complex, as well as a control version were employed. QMT is a training paradigm developed as part of an education model (Ben-Soussan, 2016; Ben-Soussan et al., 2014). QMT is a whole body motor movement training system with oral instructions (presented via a verbal script) aimed at improving attention, coordination, and creativity. The present experiment systematically replicated and slightly altered prior methods developed by Ben-Soussan et al. (2015). The PA intervention involved 3 conditions: simple motor training, complex motor training, and control. Participants were instructed to stand approximately 85 cm in front of a 85 cm X 85 cm square outlined on the floor (Quadrato motor space). Each square was labeled 1-4 (see *figure 4.1*). The simple condition consisted of stepping consistently from one box to the next in a predictable, clockwise fashion in accordance with auditory cues. The complex condition consisted of sequential trials that required selecting one of three possible step directions (left/right, forward/backward, or diagonal) in accordance with auditory cues. This complex PA protocol required an elevated state of attention, as the participant had to auditory stimuli to process information prior to producing an appropriate motoric response. The control condition consisted of seated rest (see below for details regarding each condition). The presentation of auditory stimuli was presented using a laptop computer equipped with SuperLab stimulus presentation software (SuperLab; Cedrus, San Pedro, CA).

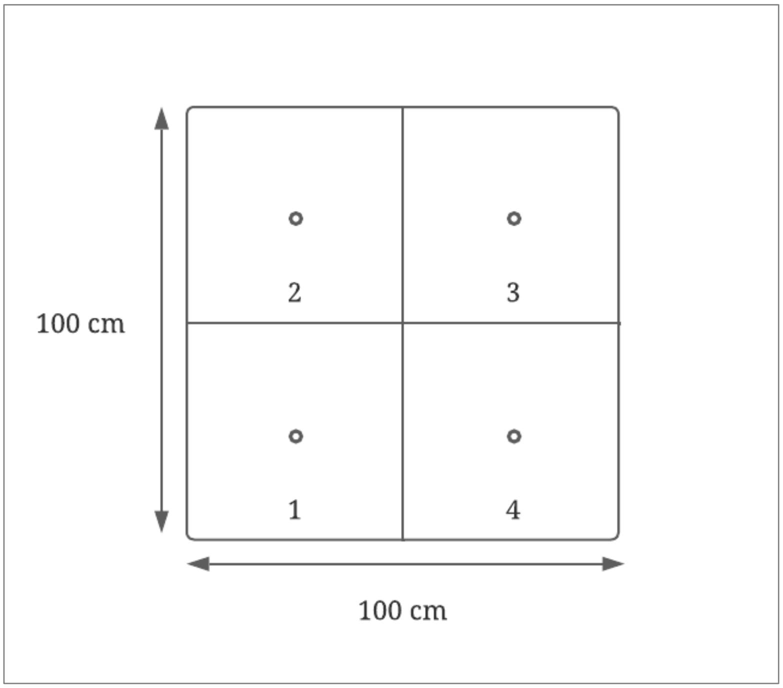


Figure 4.1. Quadrato Motor Space

Additional acceleration and stepping parameters were also assessed using the Noraxon MyoMOTION Research Pro system (Noraxon USA Inc., Scottsdale, Arizona, USA). Participants were fitted with diver slippers to ensure uniform stepping patterns. Ultium insoles, designed to transmit gait information to the Noraxon system, were placed within participants' slippers during the physical activity protocol. Insole SmartLeads were connected to inertial measurement units (IMU) bilaterally just superior to the lateral malleolus to transmit pressure data at the heel, arch, metatarsals, and hallux. A high-speed video camera, placed on a tripod approximately – cm behind the quadrato motor space, tracked and recorded participant stepping patterns during the intervention. Using the Noraxon MyoSync system, the research investigators were able to synchronously monitor video and pressure data on a laptop housing Noraxon's MR3 software. During data analysis, the variance in gait parameters, such as step time, load response time, and single support time, were used to confirm the varying level of complexity between the simple and complex physical activity conditions.

Complex motor training (CMT): Participants in the CMT condition stood approximately 85 cm in front of the 85x85 cm quadrato motor space. Movements were then made in response to prerecorded verbal instructions that directed participants to keep their eyes straight ahead and arms relaxed along the side of the body. Auditory commands were then presented followed by a tone. Participants were instructed to move to the appropriate space upon hearing the tone. Participants were also instructed to continue the sequence if an error was committed. In the CMT condition, there were a total of 3 possible directional movements that could be made (forward/backward, left/right, or diagonal). Each training trial consisted of 64 total stimuli that required a decision and appropriate movement to be made lasting 3 minutes and 45 seconds in total. 4 trials were completed in total, each separated by a 30-second rest period. Heartrate and RPE measures were collected at the conclusion of each trial.

Simple motor training (SMT): The SMT condition was identical to the CMT condition, except with a reduced number of movement choices (forward/backward, left/right). In the simple condition, the participant moved in the same manner as the CMT in regard to pace, duration, and auditory cues. In the SMT condition, the participant was instructed to step consistently from one box to the next in a clockwise fashion. The pattern of stimulus presentation remained consistent across all trials. Each training trial consisted of 64 total stimuli lasting 3 minutes and 45 seconds in total. 4 trials were completed in total, each separated by a 30-second rest period. Heartrate and RPE measures were collected at the conclusion of each trial.

Verbal training/Control (VT): The VT condition served as the control condition, where no motor movements were required nor performed. The participant was seated approximately 85 cm in front of the quadrato motor space and was presented an auditory sequence of directional stimuli, similar to the QMT and SMT conditions (these were randomized). Instead of moving to the appropriate spaces however, the participant repeated the verbal commands that were presented to him/her. For example, if the auditory command “1” was presented, the participant repeated “1” out loud and so on until the conclusion of the trial. The pace of presentation, auditory cues, and duration were consistent with the QMT and SMT conditions. 4 trials were completed in total, each separated by a 30-second rest period. Heartrate and RPE measures were collected at the conclusion of each trial.

After completing the PA protocol, participants were escorted to a table and chair within the laboratory where they were asked to rest for 3 minutes (Lambourne & Tomporowski, 2010). After the delay, the experimenter(s) administered the Digit Cancellation Task (D-CAT) which was completed in approximately 3 minutes, followed by an object location memory task.

Digit Cancellation Task (D-CAT):

After completing the PA protocol, participants were escorted to a table and chair within the laboratory where they sat and rested for 3 minutes. During this 3-minute resting period, participants were instructed to refrain from using any electronic devices. After the 3-minute period was complete, the researcher(s) administered the D-CAT. The D-CAT is a highly reliable and valid battery that is used evaluate participants’ focused attention, sustained attention/concentration, and selective attention. The D-CAT is a paper and pencil task that is easy to administer and takes approximately 5 minutes to complete, including instructions and testing (Hatta et al., 2012). The D-CAT consists of 3 trials, each administered for 60 seconds. Each trial consists of 12 rows of 50 digits. Each row consists of 5 sets of digits from 0-9 arranged in a random order, so that each digits appears 5 times in each row. Prior to the start of the test, participants were provided auditory instructions. Participants were instructed to search for a specified target digit within the grid of digits and slash it out each time it appeared. Instructions also directed participants to begin scanning at the top row and leftmost digit and scan the grid across moving on to the next row when required crossing out targets as quickly but as accurately as possible. In trial 1, there was 1 target digit. In trial 2, there were 2 target digits. In trial 3, there were 3 target digits. The start and stop of each trial were signaled verbally by the researcher.

The D-CAT consisted of a 3-page packet, with each page housing a different trial of the test. The target digits were printed in larger font than the grid and were placed at the top center of the page. The researcher presented the packet to the participants faced down and instructed them not to begin until told to do so. Directions for the D-CAT were played via a prerecorded audio script. At the conclusion of each trial, the participant placed the pencil down when signaled by the researcher.

Object Location Memory Task:

Immediately after the conclusion of the D-CAT, the researcher(s) administered the object location memory (OLM) task. The OLM task was administered via a picture book format. This object location task was a systematic replication of the same task used previously (Dulaney & Ellis, 1991; Ellis et al., 1989; Katz & Ellis, 1991). The picture book consisted of a spiral-ring binder that when opened showed two black pages divided into 4 quadrants. These quadrants were divided horizontally by a white line and vertically by the rings of the binder. When opened, the binder measured 29 by 65 centimeters. Four pictures were mounted in this two-page area, one picture centered in each quadrant. The target pictures consisted of black and white photographs of common objects against a white background (i.e., fish, strawberry, umbrella, tiger, etc.) and were categorized into nine semantic categories. The images used for the OLM task were obtained from the International Picture Naming Project Database (Szekely et al., 2004).

Participants first completed a practice trial to familiarize them with testing procedures. They viewed eight pictures shown in two sets of four. Prior to the start of the practice trial, participants were told that that after viewing all of the pictures, they would be asked to accurately free recall as many images as they could remember. Location and recognition were not mentioned nor tested during the practice trial. The researcher(s) then opened the picture book to the first set of 4 pictures, which were shown to the participant for 30 seconds. Participants were also told to name each picture out loud verbally. After 30 seconds, the researcher manually flipped the page to the next set of pictures and repeated the procedure until all practice pictures had been shown. Immediately after all pictures had been presented and viewed, participants recalled as many objects as they could remember in a 1-minute period. As a check of participants' memory and compliance of testing procedures, they were expected to correctly recall at least 6 of the 8 images within three attempts. Failure to do so resulted in exclusion from the experiment.

Following the practice trial, participants began the encoding phase of the OLM task. They viewed 60 pictures shown in 15 sets of 4. Each of the four pictures in the viewing area were from a different semantic category (people, animals, body parts, vehicles, food, things to wear, small artifacts, large artifacts, objects/phenomena in nature) and were shown to the participants for 30 seconds. Participants were not restricted to any mnemonic strategies while viewing the images. These images were different than those shown during the practice trial. At the conclusion of image presentation, participants had a 4-minute free-recall period. After the free-recall test, the researcher(s) demonstrated instructions for the relocation and recognition task using pictures from the practice set. Relocation and recognition memory were then tested. Participants were handed a set of 120 laminated pictures, including 60 targets (previously shown) and 60 non-targets (novel images), one by one in a randomized order, such that no 2 pictures from the same position follow each other. They were asked to indicate if the picture was previously shown, and if so, which quadrant it had initially appeared in. Feedback as to the correctness of responses was not provided.

Participants returned to the laboratory for sessions 2 and 3 after 24-hours and six days respectively, at the same time of day ± 1 hour for retention tests. During these sessions, participants completed a 24-hour history questionnaire to ensure stability between all testing conditions. Participants were then be given a 4-minute free-recall period to recall as many objects as they could remember. Participants then completed a recognition and relocation test of retention which was identical to the one completed during the first session. Objects presented during recognition and relocation tests were in a different randomized order than that presented previously. Feedback as to the correctness of the responses was not provided.

Interest Questionnaire:

Participants' interest in completing the study procedures was determined using the Tromso Interest Questionnaire. The Tromso Interest Questionnaire is a multidimensional scale developed in support of Four-Phase model of interest theory (Dahl & Nierenberg, 2021). The administration of the interest served as a distractor task completed after encoding and prior to immediate memory assessment to prevent the rehearsal of material encoded during the object location memory task.

Statistical analyses:

All data were analyzed via SPSS (version 29) and M*plus* (version 8) (Muthén & Muthén, 1998-2015) software. Data acquired from all 60 participants were included in the final analyses; missing data were imputed via the multiple imputation method in SPSS where necessary. M*plus* was used to analyze mediation hypotheses; all other statistically analyses were performed via SPSS.

The assumption of sphericity was tested, and Greenhouse-Geisser correction scores were used as required. An alpha-level of .05 was used as a criterion for statistical significance. Free-recall and object location memory were assessed by computing the total number of images correctly recalled and relocated during the immediate, 24-hour, and 7-day timepoints. Recognition memory was assessed using signal detection theory. Tests of recognition were scored by measuring participant response sensitivity, indicated by P(A'). P(A’) was calculated by assessing hits (target images correctly that were correctly recognized), misses (target images that were left unrecognized), false alarms (non-target images that were falsely recognized), and correct rejections (non-target images that were left unrecognized). P(A’) was then calculated using the formula:

$P(A') = \frac{1}{2} + \left(\frac{(y-x)(1+y+x)}{4y(1-x)}\right)$, where $x = \frac{false\ alarms}{non-target\ images}$ and $y = \frac{hits}{target\ images}$ (Green & Swets, 1974; Wixted, 2007).

Mediation analyses utilized the path diagrams shown in figure 4.2 that represents the statistical models used throughout the analyses. The baseline model is represented in figure 4.2a and can be expressed mathematically using the following equation: $Y = cX + e_y$, with s1 representing the variance of X (σ_x^2), and s2 representing the variance of the error of Y (σ_e^2). X represent physical activity complexity and Y represents long-term memory performance. The mediation model, shown in figure 4.2b expands upon the baseline model to include the intervening variable "M" which represents the hypothesized mediating variable of attention. This model can be expressed using the equations: $Y = c'X + bM + e_y$ and $M = aX + e_y$. In this model, s3 represents the variance of X (σ_x^2), s4 represents the variance of the mediator (σ_m^2), and s5 represents the variance of the error Y (σ_e^2). Analyses were run with three different mediating variables (omission ratio, reduction ratio, and total performance) representing attention and three different dependent variables (free-recall memory, recognition memory, and object location memory) representing long-term memory. Therefore, M and Y values inserted into the mediation analyses changed across all nine analyses. The M*plus* code used for the analyses is referenced in Appendix A.

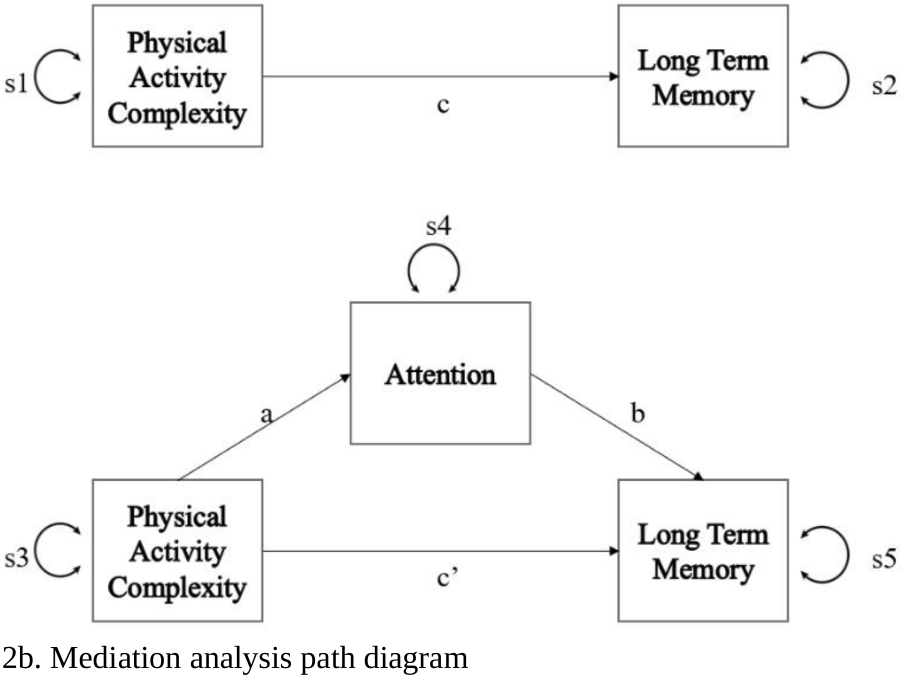


Figure 4.2a and 4.2b. Mediation analysis path diagram

4.4 Results

4.4.1 Memory

Participant demographics and anthropometric data are shown in table 4.1. Memory data were analyzed both globally and specifically across various timepoints to assess the amount of memory decay that resulted. Overall memory performance at each of the three timepoints is shown in figures 4.3, 4.4, and 4.5.

Free-Recall Memory: The effect of physical activity on free-recall memory was analyzed via separate 3(Group: control, simple, complex) x 3(Time: immediate, 24-hours, 7-day) mixed factorial ANOVA. Analyses of images free recalled immediately, 24-hours, and 7-days after encoding revealed a main effect for time, F(1.82, 57) = 6.645, $p < 0.05$, η_p^2 = 0.104, a main effect for group, F (2, 57) = 8.785, $p < 0.05$, η_p^2 = 0.236, and a non-significant Time X Group interaction, F(3.63, 103.43) = 1.642, η_p^2 = 0.054. Post-hoc pairwise comparisons with Bonferroni adjustments indicated that participants in the complex condition evidenced greater free-recall performance than those in the simple and control conditions. To assess the decay of memory across time, free-recall memory performance was isolated and compared at different time points. These comparisons included the decay from immediate to 24-hours, 24-hours to 7-days, and immediate to 7-days. Comparisons were analyzed via a 3(Group: control, simple, complex) x 2(Time: timepoint A, timepoint B) mixed factorial ANOVAs. Analyses of free recall of images immediately and 24-hours after encoding revealed a nonsignificant main effect for time, F(1, 57) = 0.303, p = .584, η_p^2 = 0.005, a significant main effect for group, F(2, 57) = 7.243, $p < 0.05$, η_p^2 = 0.203, and a nonsignificant Time X Group interaction F(2, 57) = 0.409, p = 0.666, η_p^2 = 0.014. Analyses of free-recall of images 24-hours and 7-days after encoding revealed a significant main effect for time, F(1, 57) = 10.949, $p < 0.05$, η_p^2 = 0.161, a significant main effect for group, F(2, 57) = 8.747, $p < 0.05$, η_p^2 = 0.235, and a significant Time X Group interaction F(2, 57) = 3.171, $p < 0.05$, η_p^2 = 0.10. Post hoc pairwise comparisons with Bonferroni adjustments revealed that free-recall memory decayed less from 24-hours to 7-days for participants in the complex condition; there were no significant differences between simple and control conditions.

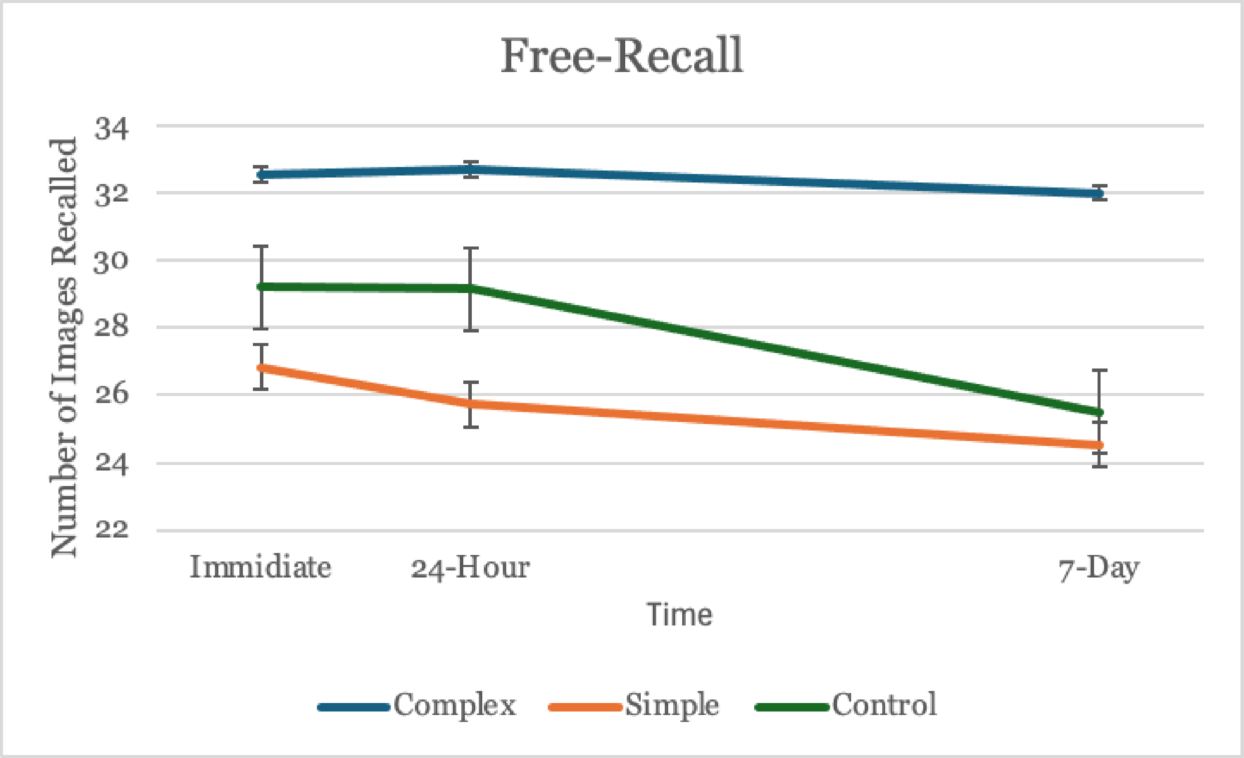


Figure 4.3. Free-recall memory

Recognition Memory: Analyses of images correctly recognized immediately, 24-hours, and 7-days after encoding revealed a main effect for time, F(1.68, 57) = 99.972, $p < 0.05$, η_p^2 = 0.637, a non-significant main effect for group, F (2, 57) = 1.282, p = 0.285, η_p^2 = 0.043, and a nonsignificant Time x Group interaction, F(3.36, 95.68) = 0.256, p = 0.905, η_p^2 = 0.009.

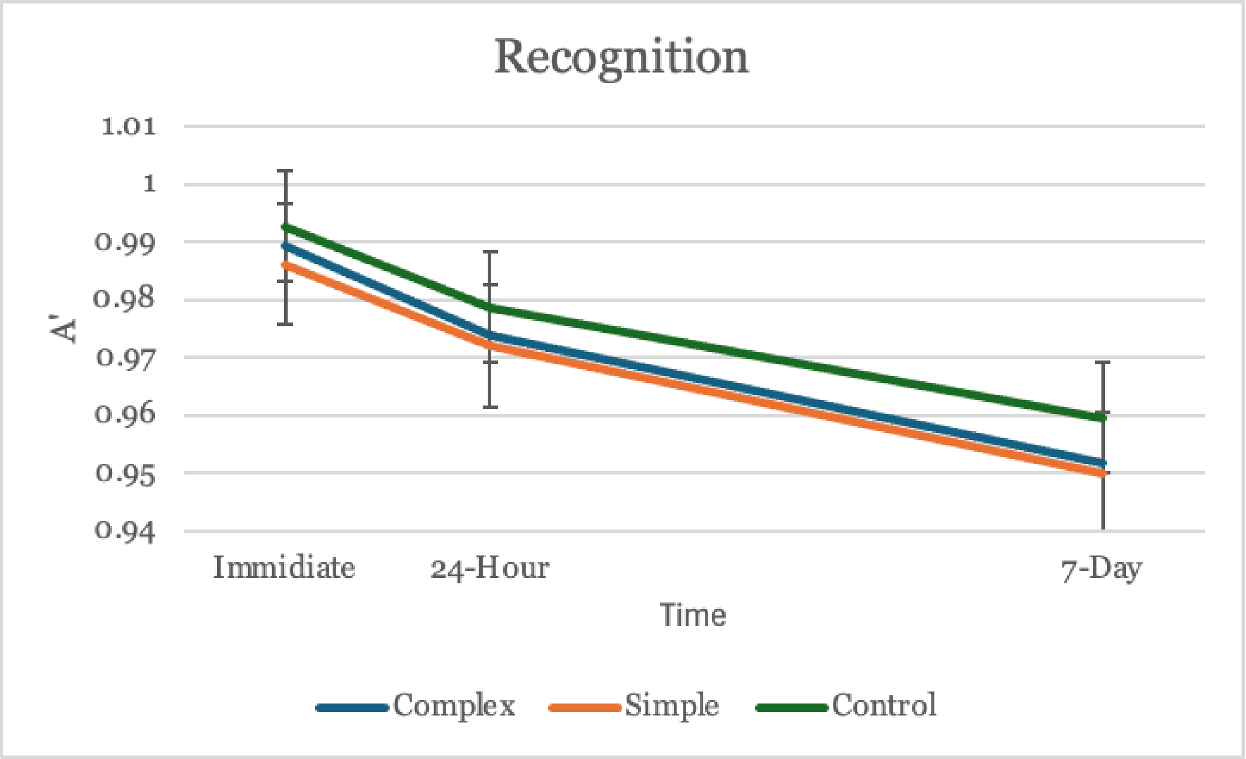


Figure 4.4. Recognition memory

Object Location Memory: Analyses of images correctly located immediately, 24-hours, and 7-days after encoding revealed a main effect for time, F(1.56, 57) = 139.090, $p < 0.05$, $\eta_p^2 = 0.709$, a nonsignificant main effect for group, F(2, 57) = 2.588, p = 0.084, $\eta_p^2 = 0.083$, and a nonsignificant Time x Group interaction, F(3.12, 114) = 0.690, p = 0.566, $\eta_p^2 = 0.024$.

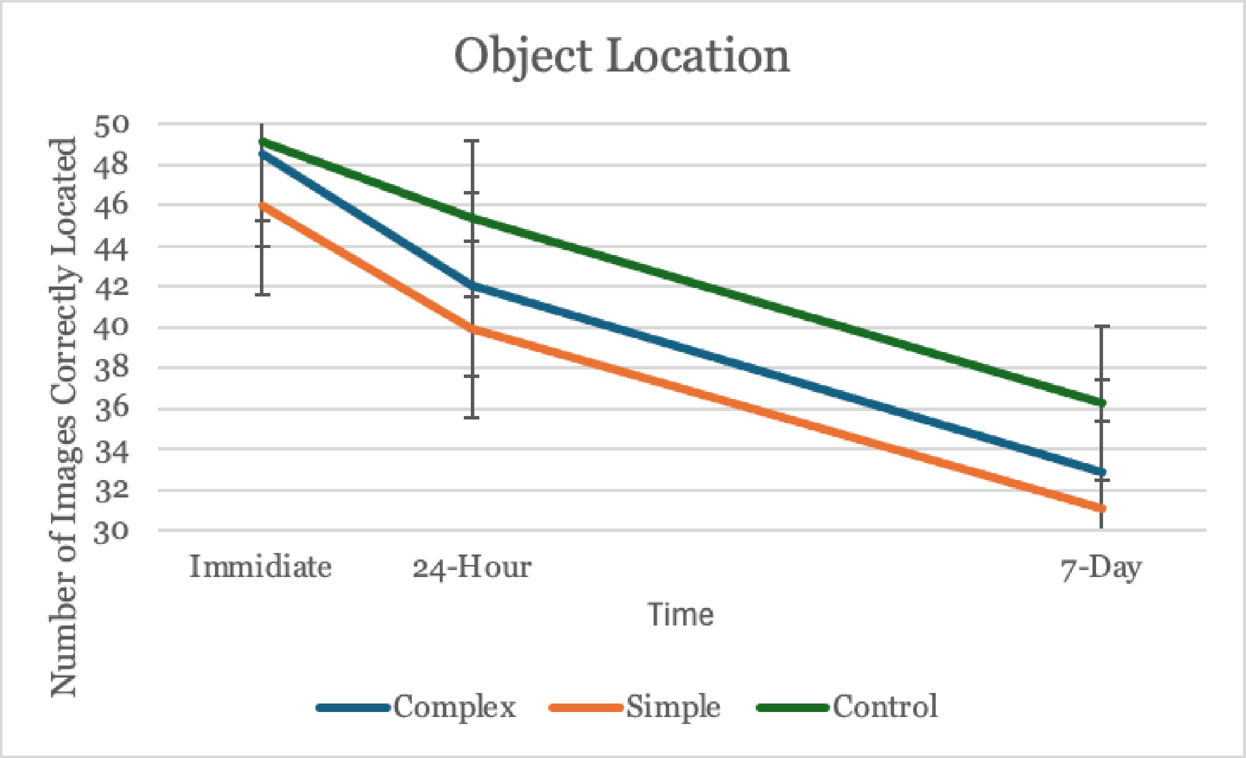


Figure 4.5. Object location memory

	Age (years)		Height (cm)		Weight (kg)	
	Female	Male	Female	Male	Female	Male
Condition	*M* ± *SD*	*M* ± *SD*	*M* ± *SD*	*M* ± *SD*	*M* ± *SD*	*M* ± *SD*
Control	20.64 ± 2.06	20.56 ± 2.01	168.02 ± 7.32	169.83 ± 10.60	65.51 ± 15.82	69.23 ± 15.41
Simple	20.38 ± 1.59	19.75 ± 2.36	167.56 ± 14.28	179.75 ± 14.90	67.12 ± 14.28	85.19 ± 7.67
Complex	21.58 ± 2.87	20.38 ± 2.62	167.54 ± 9.93	178.12 ± 12.38	61.55 ± 6.38	85.44± 20.84

Table 4.1 – Participant Anthropometrics Average Values, mean ± standard deviation.

4.4.2 Heartrate

Participants' baseline heartrates were analyzed via a one-way ANOVA. Participants' baseline heartrate data revealed no significant differences between groups, F(2, 57) = 0.04, p = 0.97, η_p^2 = 0.001, ensuring that participants in each condition had similar heartrates at baseline.

Participants' heartrates during the intervention were analyzed via a 3(Group: control, simple, complex) x 4 (Time: trial 1, trial 2, trial 3, trial 4) mixed factorial ANOVA. Analyses of participants' physical activity heartrates revealed a nonsignificant main effect for time, F(3, 171) = 1.144, p = 0.333, η_p^2 = 0.020, a significant main effect for group, F(2, 57) = 11.730, $p < 0.05$, η_p^2 = 0.292, and a nonsignificant Time X Group interaction, F(6, 171) = 0.480, p = 0.823, η_p^2 = 0.017. Post hoc pairwise comparisons with Bonferroni adjustments revealed that participants in the control condition had significantly lower heartrates during all 4 trials compared to participants in the simple and complex conditions. A 2(Group: simple, complex) x 4(Time: trial 1, trial 2, trial 3, trial 4) mixed factorial ANOVA indicated that there was no statistical difference between heart rates of participants assigned to the simple and complex conditions, $F(1,38) = 0.013$, $p = 0.911$, $\eta_p^2 = 0.000$.

4.4.3 Ratings of perceived exertion

Participants' ratings of perceived exertion were analyzed via a 3(Group: control, simple, complex) x 4(Time: trial 1, trial 2, trial 3, trial 4) mixed factorial ANOVA. Analyses of participants' ratings of perceived exertion revealed a significant main effect for time, $F(2.217, 126.368) = 15.867$, $p < 0.05$, $\eta_p^2 = 0.218$, a significant main effect for group, $F(2, 57) = 39.610$, $p < 0.05$, $\eta_p^2 = 0.582$, and a significant Time X Group interaction, $F(4.434, 126.368) = 3.401$, $p < 0.05$, $\eta_p^2 = 0.107$. Post hoc pairwise comparisons with Bonferroni adjustments revealed that participants in the control condition had significantly lower RPEs during all 4 trials compared to participants in the simple and complex conditions. A 2(Group: simple, complex) x 4(Time: trial 1, trial 2, trial 3, trial 4) mixed factorial ANOVA indicated that there was no statistical difference between the RPEs of participants assigned to the simple and complex conditions, $F(1, 38) = 2.019$, $p = 0.164$, $\eta_p^2 = 0.050$.

4.4.4 Attention

Participants' digit cancellation task data are shown in table 4.2. Digit cancellation task outcomes include omission ratio, reduction ratio, and total performance. Omission ratio reflects a measure of sustained and selective attention and was calculated using the formula $\frac{number\ of\ missed\ targets}{number\ of\ digits\ \ inspected} * 100$. Reduction ratio reflects the durability of focused, sustained, and selective attention, as well as a measure of mental fatigue and was calculated using the formula $\frac{number\ of\ digits\ inspected\ in\ trials\ 2\ and\ 3}{number\ of\ digits\ inspected\ in\ trial\ 1}$. Total performance reflects the total number of digits that are inspected that reflects information processing speed, focused, and sustained attention and was calculated using the formula $(number\ of\ \ digits\ inspected\ in\ trial\ 1) +$

$(number\ of\ digits\ inspected\ in\ trial\ 2) + (number\ of\ digits\ inspected\ in\ trial\ 3)$ (Hatta et al., 2012). Omission ratio data were analyzed via a one-way ANOVA. Participants' omission ratio data revealed no significant differences between groups, F(2, 57) = 0.46, p = 0.63, η_p^2 = 0.02. Participants' reduction ratio data revealed no significant differences between groups, F(2, 57) = 0.44, p = 0.65, η_p^2 = 0.02. Participants' total performance data revealed no significant differences between groups, F(2, 57) = 0.87, p = 0.43, , η_p^2 = 0.03.

	Digit Cancellation Task Outcomes		
	Omission Ratio	Reduction Ratio	Total Performance
Condition	*M* ± *SD*	*M* ± *SD*	*M* ± *SD*
Control	1.25 ± 0.81	1.37 ± 0.15	852.65 ± 138.0
Simple	1.41 ± 0.73	1.42 ± 0.21	823.9 ± 140.74
Complex	1.20 ± 0.67	1.36 ± 0.23	889.6 ± 190.05

Table 4.2. Digit cancellation task average values, mean ± standard deviation

4.4.5 Mediation

Free-recall: Model fit for the mediation analysis of total performance showed that the model was saturated: Chi-Square Test of model fit = 0.0 (p < 0.00); RMSEA = 0.0; CFI = 1; TLI = 1; and SRMR = 0.0. Information criteria were high, with AIC = 1320.921 and BIC = 1339.770. The total reported direct effect of total performance was significant, with a coefficient of 3.043 and p = 0.001. The total reported indirect effect of total performance was nonsignificant, with a coefficient of 0.207 and p = 0.475, effects in total explaining 32% of the variance in performance.

Model fit for the mediation analysis of omission ratio showed that the model was saturated: Chi-Square Test of model fit = 0.0 (p < 0.00); RMSEA = 0.0; CFI = 1; TLI = 1; and SRMR = 0.0. Information criteria were high, with AIC = 709.395 and BIC = 728.244. The total reported direct effect of omission ratio was significant, with a coefficient of 3.249 and p = 0.001. The total reported indirect effect of omission ratio was nonsignificant, with a coefficient of 0.001 and p = 0.995.

Model fit for the mediation analysis of reduction ratio showed that the model was saturated: Chi-Square Test of model fit = 0.0 (p < 0.00); RMSEA = 0.0; CFI = 1; TLI = 1; and SRMR = 0.0. Information criteria were high, with AIC = 523.755 and BIC = 542.604. The total reported direct effect for reduction ratio was significant, with a coefficient of 3.249 and p = 0.001. The total reported indirect effect of reduction ratio was nonsignificant, with a coefficient of -0.037 and p = 0.813

Free-recall memory mediation analyses with reported coefficients and standard errors for each attentional mediator are shown in figure 4.6. Taken together, these results indicate a moderate model fit across the board and support the hypothesis that there is a relationship between physical activity and free-recall memory, as confirmed via the ANOVA analyses reported earlier. However, consistent nonsignificant results suggest that attentional processes do not mediate this relationship.

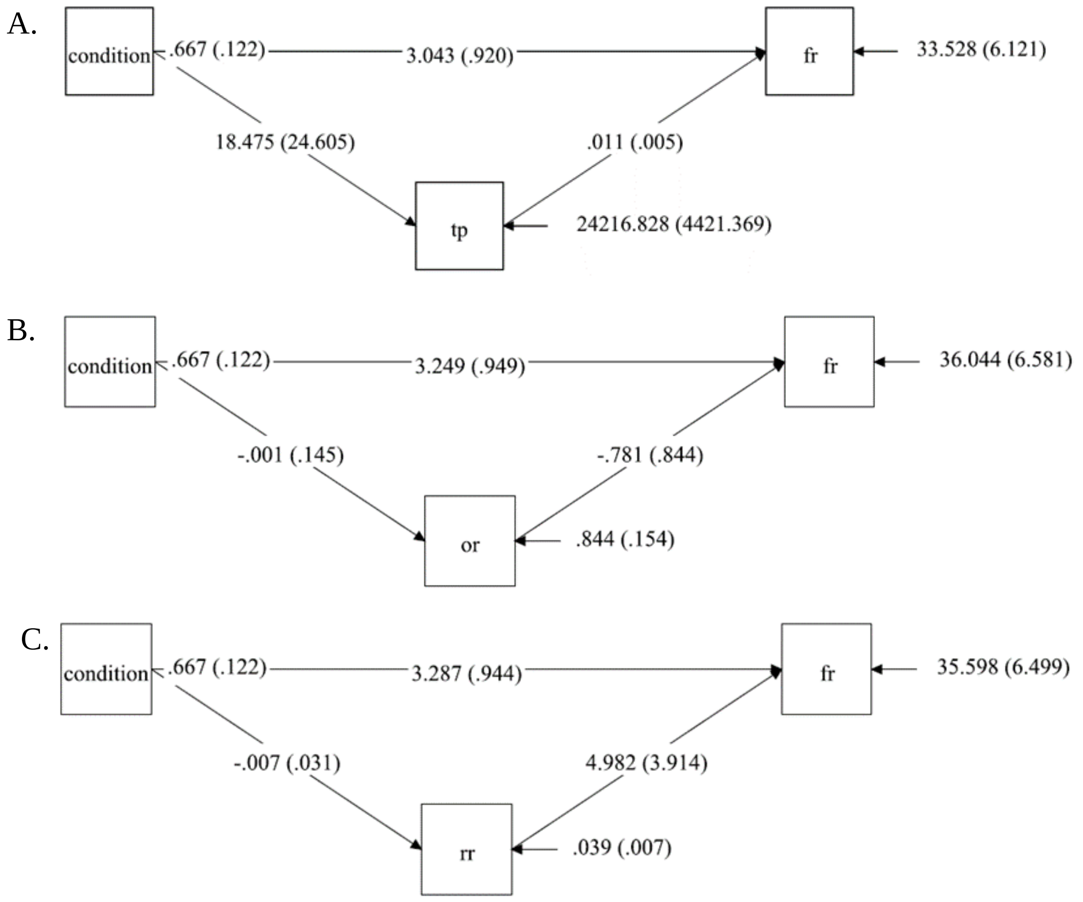


Figure 4.6 – Free-recall mediation analyses; coefficients and standard error for each attentional mediator are reported. A reflects total performance data, B reflects omission ratio data, and B reflects reduction ratio data.

Recognition: Model fit for the mediation analysis of total performance showed that the model was saturated: Chi-Square Test of model fit = 0.0 (p < 0.00); RMSEA = 0.0; CFI = 1; TLI = 1; and SRMR = 0.0. Information criteria were low, with AIC = -158.01 and BIC = -139.18. The total reported direct effect of total performance was nonsignificant, with a coefficient of -0.005 and p = 0.243. The total reported indirect effect of total performance was nonsignificant, with a coefficient of 0.001 and p = 0.478, effects in total explaining 25% of the variance in performance.

Model fit for the mediation analysis of omission ratio showed that the model was saturated: Chi-Square Test of model fit = 0.0 (p < 0.00); RMSEA = 0.0; CFI = 1; TLI = 1; and SRMR = 0.0. Information criteria were moderate, with AIC = 57.76 and BIC = 76.6. The total reported direct effect of omission ratio was nonsignificant, with a coefficient of -0.004 and p = 0.345. The total reported indirect effect of omission ratio was nonsignificant, with a coefficient of 0 and p = 0.995.

Model fit for the mediation analysis of reduction ratio showed that the model was saturated: Chi-Square Test of model fit = 0.0 (p < 0.00); RMSEA = 0.0; CFI = 1; TLI = 1; and SRMR = 0.0. Information criteria were low, with AIC = -125.687 and BIC = -106.838. The total reported direct effect of reduction ratio was nonsignificant, with a coefficient of -0.004 and p = 0.36. The total reported indirect effect of reduction ratio was nonsignificant, with a coefficient of 0 and p = 0.827.

Recognition memory mediation analyses with reported coefficients and standard errors for each attentional mediator are shown in figure 4.7. Inconsistent model fit across these analyses aligns with the trending, but nonsignificant findings for recognition long-term memory ANOVA analyses reported earlier.

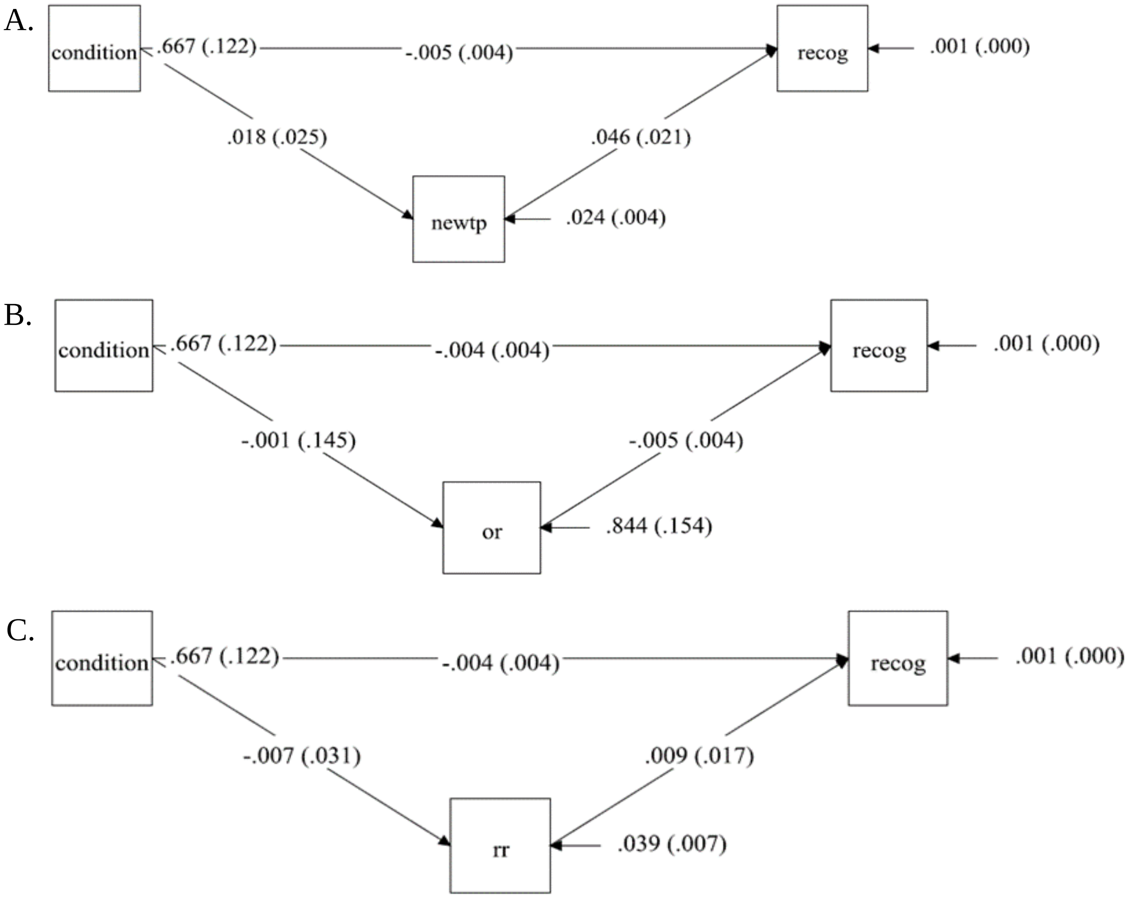


Figure 4.7 – Recognition mediation analyses; coefficients and standard error for each attentional mediator are reported. A reflects total performance data, B reflects omission ratio data, and C reflects reduction ratio data.

Object location: Model fit for the mediation analysis of total performance showed that the model was saturated: Chi-Square Test of model fit = 0.0 (p < 0.00); RMSEA = 0.0; CFI = 1; TLI = 1; and SRMR = 0.0. Information criteria were high, with AIC = 1353.976 and BIC = 1372.826. The total reported direct effect of total performance was nonsignificant, with a coefficient of -1.981 and p = 0.102. The total reported indirect effect of total performance on was nonsignificant, with a coefficient of 0.256 and p = 0.477, effects in total explaining 22% of the variance in performance.

Model fit for the mediation analysis of omission ratio showed that the model was saturated: Chi-Square Test of model fit = 0.0 (p < 0.00); RMSEA = 0.0; CFI = 1; TLI = 1; and SRMR = 0.0. Information criteria were high, with AIC = 740.251 and BIC = 759.100. The total reported direct effect of omission ratio was nonsignificant, with a coefficient of -1.727 and p = 0.16. The total reported indirect effect of omission ratio was nonsignificant, with a coefficient of 0.002 and p = 0.995.

Model fit for the mediation analysis of reduction ratio showed that the model was saturated: Chi-Square Test of model fit = 0.0 (p < 0.00); RMSEA = 0.0; CFI = 0; TLI = 1; and SRMR = 0.0. Information criteria were high, with AIC = 759.100 and BIC = 576.348. The total reported direct effect of reduction ratio was nonsignificant, with a coefficient of -1.748 and p = 0.162. The total reported indirect effect of reduction ratio was nonsignificant, with a coefficient of 0.023 and p = 0.824

Object-location memory mediation analyses with reported coefficients and standard errors for each attentional mediator are shown in figure 4.8. Across all attentional mediators, the model fit and reports of statistical significance do not support the hypothesized attentional mediation between physical activity and object location memory performance.

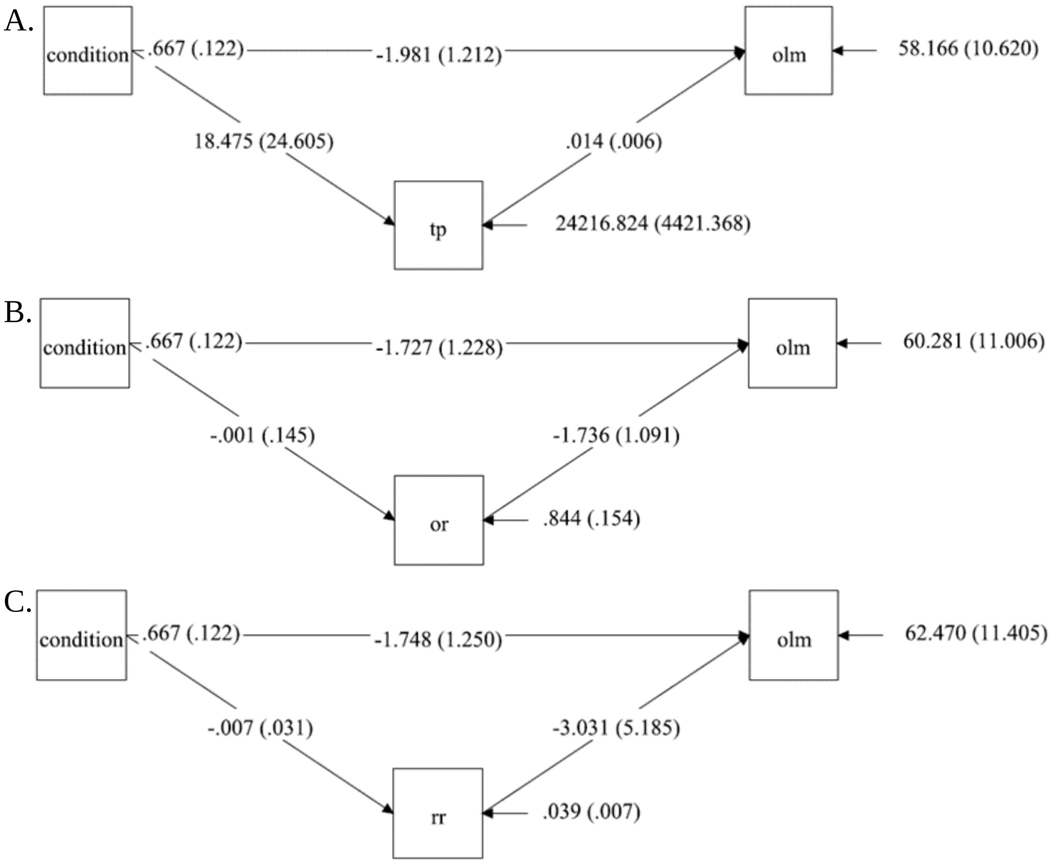


Figure 4.8 – Object location mediation analyses; coefficients and standard error for each attentional mediator are reported. A reflects total performance data, B reflects omission ratio data, and C reflects reduction ratio data.

4.4.6 Physical activity

Participants' physical activity characteristics and gait parameters were analyzed via an independent samples t-test. Stride time, which is operationally defined as the amount of time between two consecutive heel strikes by the same leg (Richards et al., 2013), and cadence, which quantifies the rate of steps displayed across a period of time usually reported in minutes (Tudor-Locke et al., 2021) values were analyzed. Because participants in the control condition did not perform any physical activity, only participants in the simple and complex condition were used for data analyses. Analyses of gait parameters revealed that participants assigned to the simple condition had a significantly shorter stride time, t(38) = -4.94, $p < 0.05$, compared to those assigned to the complex condition. There were no statistical differences in cadence between groups, t(38) = 2.95, p = 0.27.

4.4.7 Interest

Participant interest scores are shown in table 4.3.

	General Interest	
	Physical Activity Intervention	Memory Task
Condition	*M* ± *SD*	*M* ± *SD*
Control	3.83 ± 1.30	4.70 ± 0.98
Simple	4.18 ± 1.08	5.05 ± 1.70
Complex	4.50 ± 0.70	4.75 ± 1.18

Table 4.3. General interest values for physical activity intervention and memory task, mean ± standard deviation

4.4.8 Godin Leisure-Time Exercise Questionnaire

Participants' baseline Godin leisure-time exercise questionnaire scores were analyzed via a one-way ANOVA. Analyses of Godin leisure-time exercise scores revealed no significant differences between groups, F(2, 57) = 0.48, p = 0.48, $\eta_p^2 = 0.03$, ensuring that participants in each condition had similar weekly physical activity patterns.

4.5 Discussion

The aim of the present experiment was to examine the effects of an acute bout of physical activity on young adults' episodic free-recall memory, recognition memory, and object location memory. The primary finding of the experiment revealed that young adults who completed a complex bout of physical activity demonstrated greater and more durable free-recall memory, but not recognition nor object location memory, compared to those who completed the simple physical activity or control condition.

A secondary aim of the present study was to examine the role of attention as a potential mediator between physical activity and long-term memory. Attention refers to a state of conscious awareness during which an individual can respond to focal stimuli, often excluding other stimuli. Results revealed that attention did not significantly mediate the relationship between physical activity and long-term memory among young adults, failing to support the hypothesis that attention would mediate the relationship between physical activity and long-term memory.

The final aim of the study was to determine if physical activity complexity differentially impacted memory processes. The results support the hypothesis that participants who completed a complex bout of physical activity would produce the largest mnemonic benefits experiencing less free recall decay than the simple and control conditions seven days after encoding. Physical activity did not significantly affect recognition and object-location memory, suggesting that the impact of physical activity is not universal across long-term memory processes.

Contemporary psychological theories of memory and attention along with current advances in the neuropsychology of memory provide possible explanations as to why physical activity has differential effects on memory processes.

4.5.1 Free-Recall Memory

The primary result of the present experiment indicated that physical activity prior to encoding resulted in enhanced free-recall episodic memory. These findings are in line with existing evidence that physical activity has selective effects on long-term memory. For example, Coles & Tomporowski (2008) found that when moderate intensity exercise (compared to no exercise) preceded encoding, participants demonstrated improved performance on free-recall suggesting better facilitation of information consolidation into long-term memory. Similarly, Pesce et al. (2009) and Labban & Etnier (2011) noted that exercise performed before learning resulted in better recall performance and facilitated long-term memory storage. When exercise followed encoding, there were no changes in tests of delayed recall memory as reported by Hötting et al. (2016) and Tomporowski et al. (1987). Collectively, these findings support the notion that exercise induces selective effects on certain long-term memory processes. More specifically, existing evidence suggests that when physical activity precedes memory encoding, the greatest effect is exhibited on free-recall memory (Loprinzi et al., 2021; Qazi et al., 2024). These results are in line with these data confirming the selective effects of physical activity on long-term memory. The selective effects of physical activity on long-term episodic memory processes may in part be explained by contemporary theories of long-term memory as discussed in chapter two.

Cognitive theories

Several theories of long-term memory have been established over the last century. Richard Atkinson and Richard Shiffrin's Search for Associative Memory model posits that items held in the short-term memory store serve as a buffer that influences information that is transferred into the long-term memory stores. When tasked with retrieving information from long-term memory, indicative of free-recall memory tests, individuals undertake a search of stored memory traces. Depending on the strength of the association of the target items in the long-term memory store can result in the successful retrieval of information from long-term memory. This model highlights that free-recall is not a passive memory process, rather an active process that relies on the association and connections between items (Malmberg et al., 2019). The strength of the association between items in the long-term memory store are highlighted in trials utilizing interference (Abel & Bäuml, 2019)) and contextual cues (Lohnas et al., 2011), both integral components of the Search for Associative Memory model.

Neurophysiological theories

It is hypothesized that physical activity results in systemic changes in physiological arousal that impact executive processing, mental performance, and cognitive function (McGaugh, 2013, 2015; McMorris, 2016; Robison & Brewer, 2020). Thus, it is plausible that in the present experiment, physiological changes as a result of physical activity influence the strength of item and context memory traces stored in long-term memory, which facilitate free-recall memory processes as suggested by the Search for Associative Memory model. Physical activity-induced arousal has long been posited as a potential mechanism to modulate the relationship between physical activity and memory. Changes that occur in the brain as a result of physical activity have been linked to changes in long-term memory. Investigators have predicted that during the performance of gross motor physical activities, improvements in cognitive function are present driven by changes in brain neurotransmitter systems. The initiation of physical activity results in the synthesis of catecholamines in the sympathetic-adrenal-system axis in the brainstem. With continuous physical activity, norepinephrine and dopamine are released from the adrenal medulla which are proposed to influence brain networks that are responsible for information-processing pathways (Lambourne & Tomporowski, 2010). These pathways are responsible for the acquisition, storage, and retrieval of long-term memory processes including free-recall.

Davey (1973) postulated an inverted-U relationship between exercise and cognition, such that moderate intensity exercise would induce most optimal cognitive performance, whereas high and low intensity exercise would have detrimental effects on cognitive performance. Extremely high and low levels of arousal can disengage the dorsolateral prefrontal cortex which alters the interaction between attentional networks. The inhibited interaction between attentional networks can lead to lower levels of cognitive performance (Dehais et al., 2020). In line with the inverted-U hypothesis, physical activity-induced arousal is purported to enhance long-term memory processes by altering the signal-to-noise ratio of neurological systems which in turn, enhances attentional control and decision making (McMorris et al., 2015). A heightened signal-to-noise ratio may also improve encoding and explain the reductions in individuals' response times during physical activity (Lambourne & Tomporowski, 2010). Therefore, the moderate intensity physical activity intervention that was utilized in the present experiment may have produced arousal-induced benefits that resulted in more durable free-recall memory performance.

The effects of physiological arousal on behavioral outcomes have been well established over the last few decades. Animal studies provide compelling evidence that have advanced the notion that arousal enhances the storage of memories. Stress-induced activation of the amygdala and its associated networks play a critical role to ensure that any emotionally driven event is consolidated into long-term memory (McGaugh, 2013; Roozendaal & Hermans, 2017). Collectively, these contemporary neurophysiological theories provide convergent evidence and better explain the mechanisms by which physical activity improve the processes underlying free-recall memory.

4.5.2 Recognition Memory

Physical activity prior to encoding did not significantly affect recognition memory in the present experiment. This finding fails to support the hypothesis that physical activity would have a generalized effect on long-term memory. Recognition memory was hypothesized to improve as a function of physical activity. These null results may reflect the conclusions drawn from a recent meta-analysis (Qazi et el., 2024) and models of neuropsychological mechanisms.

As discussed in chapter three, Qazi et al. (2024) reported that physical activity prior to encoding did significantly influence free-recall memory but not recognition memory. The lack of effects on recognition memory may be explained by several cognitive and neurophysiological mechanisms.

Cognitive theories

The lack of significant effects on recognition memory processes may be explained by the Retrieving Effectively from Memory single-process Model. This model proposed by Richard Atkinson and Richard Shiffrin (Atkinson & Shiffrin, 1968) focused on the importance of item familiarity, which is the key component that drives recognition memory. Unlike free-recall memory, recognition memory processes do not rely heavily on remembrance, rather distinguishing between unfamiliar and novel information. During the process of encoding, there exists “noise” that influences the how well information is learned. This “noise” results from background information that may be present during learning conditions such as environment, the mood of the individual, levels of arousal, interest, or motivation, etc. The noise derived from such conditions therefore influences memory retrieval (Criss & Shiffrin, 2004). In the current experiment, physical activity occurred prior to encoding. It is plausible that if physical activity occurs after encoding.

In addition to the Retrieving Effectively from Memory Model proposed by Atkinson and Shiffrin, other theories of recognition memory may also explain the results of the present experiment. The Signal-Detection Theory posits that decisions are made based on the strength of a memory signal in relation to a decision criterion (Macmillan & Creelman, 2004). Signal detection typically involves two equal variance Gaussian normal distributions in which one distribution represents targets and the other representing non-targets. Signal detection theory also hypothesizes a decision criterion. A stimulus that generates a memory trace that exceeds the decision criterion is declared ‘old’ or previously seen. Alternatively, a stimulus that generates a trace that is below the criterion is declared ‘new’ or novel. This single process-model of recognition memory supports item familiarity as opposed to item recollection (Wixted, 2007). Physical activity has implications in altering sensitivity with respect to decision making (Lefferts et al., 2019). Physical activity may influence response criteria, shifting the ‘new/old’ model from an equal to an unequal variance which can directly impact decision making (Wixted, 2007). It is plausible that the physical activity intervention used in the present experiment did not elicit an adequate shift in ‘old/new’ variances, which may have been due to the characteristics of the intervention as well as individual differences.

In contrast with the Retrieving Effectively from Memory Model and Signal-Detection Theory Model of recognition memory, the Dual-Process theory holds that recognition memory is characteristic of two central processes, recollection and familiarity (Macmillan & Creelman, 2004). This more recent model holds that recollection either occurs or not, whereas familiarity is continuous and overseen by signal detection processes. According to this theory, no decision criteria based signal detection need to be made for recollection. If recollection fails, then familiarity based decisions are made. Familiarity is thus thought to be a backup process should recollection fail (Macmillan & Creelman, 2004).

The role of the temporal relation between encoding on long-term memory has been discussed extensively in the literature. Researchers have drawn conflicting conclusions concerning the role of physical activity performed prior to or following encoding (Loprinzi et al., 2019; Qazi et al., 2024; Roig et al., 2013). The meta-analytic findings of Qazi et al. (2024) presented clear evidence for a dissociation of LTM performance driven by the temporal relation between physical activity and encoding. Other research findings are in line with the meta analytical findings that acute bouts of physical activity post-encoding induce robust improvements in recognition memory. When participants contracted their arm muscles during and after encoding phase of a memory test, delayed recognition memory for the words as enhanced compared to when they did not exert any physical effort (Nielson et al., 1996). In a more recent experiment, participants demonstrated improved recognition memory after an acute bout of moderate-to-vigorous cycling post-encoding compared to pre-encoding. The results demonstrated that acute self-perceived hard cycling post-learning, but not pre-learning, improved recognition memory (Venezia et al., 2023). Consistent with the results of the present experiment, others have also indicated improved recognition memory for images as a result of post-encoding physical activity (Segal et al., 2012; Weinberg et al., 2014). It is plausible therefore that physical activity before encoding could alter individual arousal levels impacting attention and in turn, working memory enhancing long-term memory processes.

Neurophysiological theories

Physiological arousal incited by physical activity may impact recognition memory processes. Tests of recognition memory rely in part on judgments and familiarity. Physical activity-induced arousal may therefore influence performance on such tasks of recognition. Neurophysiological models of long-term memory implicate the biological response that is derived from physical movements. These models suggest that recognition based on item-familiarity may be modulated by the release of stress hormones resulting in physiological changes throughout the central nervous system. Because adrenal stress hormones are implicated in the process of converting labile short-term memory traces into permanent long-term memory traces, it is possible that these hormones may influence memory storage and subsequent retrieval, especially the recognition of previously encoded items (McGaugh, 2015). Considerable research in the area of stress and emotion has linked arousal as a primary modulator of storage and memory acquisition. Similar to the pathways involved in free-recall memory, existing evidence suggests that a moderate level of arousal is optimal for certain complex tasks that involve making decisions/judgements or complex visual discrimination. Arousal is characterized by increases in the release of adrenal stress hormones. The release of stress hormones is involved with increased noradrenergic activity which has been identified as an important mechanism via which arousal enhances memory function (Diamond et al., 2007; LaLumiere et al., 2017). Physical activity that exceeds the threshold of sufficient intensity is classified as a physiologically arousing stimulus (McMorris, 2016). Increased arousal before and after memory encoding has been shown to improve long-term memory. Therefore, the incorporation of physical exercise as a stressor can activate similar pathways (increasing circulating catecholamines and noradrenergic signaling) that are induced via alternative physical or psychological stressors. Because these pathways are directly involved in long-term memory enhancement, acute physical activity as a stressor is effective at facilitating memory formation (McMorris, 2021; Roig et al., 2016).

Extensive research conducted on animal models is also in line with psychological and neurophysiological theories of memory. As discussed in chapter 3, the evidence presented via animal models by James McGaugh has shown that stressful events play a role in the activation of the amygdala, which modulates hippocampal activity. Given the role of the hippocampus in memory formation, hippocampal activation via the pathways of the amygdala can lead to enhanced memory encoding for emotionally arousing events. The "emotional hub" of the brain, the amygdala processes emotional experiences such as fear, excitement, shock, etc. and tags memories as emotionally meaningful. When the amygdala is activated as a result of an emotional event, it signals to hippocampal regions to strengthen the encoding and storage of the emotionally significant memory traces. This pathway between the amygdala and hippocampus is associated with enhanced memory consolidation from labile traces in working memory to long-term memory, making them more likely to be remembered (McGaugh, 2004, 2015).

4.5.3 Object-location Memory

Object location memory was hypothesized to improve following a bout of physical activity. This hypothesis was prompted by existing evidence showing improvements in object location memory following an acute bout of physical activity (Erickson et al., 2009, 2011). In the present experiment, physical activity prior to encoding did not significantly affect object-location memory in young adults. This result is similar to the data obtained by Ramirez Butavand et al. (2023), who assessed spatial memory among healthy young adults and found that a 25-minute bout of cycling after encoding improved long-term spatial memory retention (Ramirez Butavand et al., 2023). Object-location memory is categorized as a subcomponent of spatial episodic memory that consists of specific processes such as information about the location, orientation, direction of objects, and the binding of these objects to memory stores (van Asselen et al., 2009). Evidence acquired via neuropsychological and individual difference experiments may explain the failure of the present experiment to support the hypothesis that acute physical activity would improve long-term object location memory.

Neuropsychological mechanisms

Functional characteristics of object-location memory make it unique from other memory processes in that spatial memory relies on coordinated patterns of activity in such brain regions as the hippocampus, prefrontal, and parietal cortices (Eichenbaum & Cohen, 2014). Object-location memory differs from spatial memory in that it does not involve storing sequences of spatial decisions or temporally ordered spatial information, both of which are necessary for tasks involving navigation. Object-location memory simply involves a representation of where things are located in space. Representational processes apply to small-space environments (where objects are located in a room) or large-space environments (where objects are located in a house). Importantly, encoding mechanisms are similar in both settings. When encoding the location of objects, individuals also need to know which additional features such as shape, color, and identity correspond to those locations. The role of perception is crucial to the object-location memory. In order for objects and locations to be coded, they need to be processed. There is a specialized route within the visual cortex that projects to the posterior inferior temporal cortex which is central for object recognition (Allen, 2004; Conway, 2018; Fan et al., 2020). This pathway is evidenced via lesion studies in humans, in which damage to the temporal areas in the ventral stream causes the inability to visually recognize objects (Bennett, 2023; Milner & Goodale, 1997).

A dual-memory model proposed by Yonelinas et al. (2019)provides a linkage among the operations underlying object location memory. Existing evidence supports the distinction between short- and long-term object location memory stores. Early animal models point to distinct spatial memory processes that are classified as either short-term (90 minutes) or long-term (24 hours or longer) (Vogel-Ciernia & Wood, 2014). Evidence for the impact of physical activity on object-location memory has also been presented via animal models. Several experiments conducted with rats provide physiological evidence that physical activity enhances spatial memory. These improvements result via mechanisms of enhanced synaptic plasticity (Shih et al., 2013), neuron density (Uysal et al., 2005), hippocampal neurogenesis (Gomes da Silva et al., 2012), enhanced brain-derived neurotrophic factor levels (Hopkins et al., 2011), and other molecular mechanisms (Cassilhas et al., 2012). Additional evidence for a short-term spatial store is grounded within a working memory model proposed by Baddeley and Hitch (1974) which hypothesizes a multicomponent memory stores. These short-term storage systems contain the visuospatial sketchpad which briefly holds and manipulates information regarding the appearance and location of objects in space. Because this information is malleable, it is classified as a distinct component of working memory. Existing evidence suggests that acute bouts of exercise improve working memory among other components of executive function, especially among young adults (Chang et al., 2012b; Loprinzi et al., 2019; Roig et al., 2013b). Changes in working memory have been predicted to facilitate long-term memory functions. It is plausible that physical activity-induced changes in the current paradigm did not impact specific components of working memory. The visuospatial components of working memory in turn may not have changed as a function of physical activity leading to no significant changes in object location memory across time.

Individual differences

There are robust individual differences in long-term memory processes. There is some evidence to suggest that individual differences in the ability to allocate attention during encoding are important for individual differences in long-term memory. Components of information processing including working memory and attention control contribute to these differences in long-term memory processes. Other mediating factors such as age, intelligence, gender, etc. are also associated with long-term memory processes. Correlational and experimental studies provide evidence that individual differences in long-term memory are interlinked with other cognitive abilities (Unsworth, 2019). Existing evidence broadly explains how individuals behave differently on tests of memory, indicating a large variation with respect to memory abilities. The Tetrahedral Model of Memory suggests four interacting factors. These factors include encoding conditions, to-be-remembered materials, retrieval conditions, and subject factors. These variables interact strongly with one another as well as additional factors highlighting the enhanced variability between individuals (Jenkins, 1979). Due to these variations and the multiple mechanisms involved in long-term memory processing, it is often the case that some individuals show changes in memory performances whereas others do not. It is plausible that the individual differences among the participants in the present experiment resulted in improvements in free-recall memory processes, but not recognition nor object-location memory processes. Based on the interrelation between long-term memory and attention, it is also likely that individual difference factors partially failed to support the a priori hypothesis such that attentional mediation between physical activity and long-term memory failed to reach significance.

The lack of significant effects with respect to object location memory may also be explained via the Theory of Effortful Processing proposed by Hasher and Zacks (1979). This framework proposes a that memory encoding operations vary in their attentional requirements. Memory operations that deplete minimal attentional resources from a limited-capacity attentional pool are classified as an automatic process. Effortful operations require greater attentional allocation and are initiated under conscious awareness. The intentional nature of effortful processing allows it to benefit from practice, whereas automatic processing does not benefit from rehearsal and proceeds consistently throughout (Hasher & Zacks, 1979). In line with this theory, memory for location is hypothesized to be encoded under automatic processing into long-term memory. Therefore, automatically processed information that receives reduced attentional resources for encoding may result in more rapid decay. Automatically encoded information may also be remembered less over time due to the lack of specificity and contextual binding during encoding, which typically results in improved memory traces. Though the location for the spatial context of items may initially be robust, may not be durable over time (Dulaney & Ellis, 1991).

4.5.4 Attention

Previous studies have examined the relationship between physical activity and attentional processes including selective, focusses, and sustained attention. These experiments have shown significant findings among children (Alvarado Melo et al., 2024; de Greeff et al., 2018b; Fedewa et al., 2021), adults (Budde et al., 2008; Haverkamp et al., 2020; Kao et al., 2018), and older adults (Chen et al., 2020; Nuzum et al., 2020). Several theories of memory encoding have addressed the role of attentional processes. Few experiments, however, have explore the role of attention as a potential mediator between the physical activity-memory relationship.

The a priori hypothesis central to the present experiment was developed in line with existing theory and evidence. In this experiment, mediation analyses were employed to assess whether attentional processes that underlie physical activity impact long-term memory outcomes. The results for the mediating role of all attentional processes were nonsignificant, suggesting that under the conditions employed in the present experiment, attention did not mediate the effects of physical activity on long-term memory.

Neuropsychological and Neurophysiological Theories

The failure to support the hypothesis may be attributed to several factors. Theories of attention discussed previously in chapter 2 presented theoretical evidence regarding the multifaceted makeup of attention and the differential effects that physical activity has on these components. Theories of arousal propose that physical activity-induced arousal enhances cognitive processing by altering the signal-to-noise ratio of neurological systems which may enhance basic cognitive processes such as attention and executive function. Grounded primarily as a physiological rationale, Yerkes and Dodson's theory of arousal posits that acute physical activity temporarily changes neurobiological properties which in turn primes learning leading to improved cognition (Chang et al., 2012a) as well as academic achievement (Tomporowski et al., 2015). This theory suggests that an inverted-U relationship exists between arousal and performance, such that a moderate level of arousal during encoding produces the largest cognitive benefits (Davey, 1973). The arousal induced from low-moderate physical activity in the present study therefore may not have reached a sufficient threshold to prime the participants' neurobiological properties for enhanced cognition leading to null attentional outcomes.

From an alternative perspective, cognitive-energetic theory, which integrates both physiological and psychological concepts, could also explain the present outcomes. Proponents of the cognitive-energetic approach imply that traditional information-processing models alone are not sufficient in explaining human behavior because they fail to take “wet” biological and affective properties into consideration and only focus on “dry,” computer-like properties. These “wet” properties are thought to underlie top-down control of behavioral output including the attention (Koelega, 1996). The overall efficiency of information-processing within the cognitive-energetic model is thought to influence both process and state factors. The cognitive-energetic model (*figure 4.9*) consists of three different levels; a computational or cognitive level, an energetic level, and an evaluation level (Sergeant, 2000). Central to the present study is the second level, which consists of pools of effort, arousal, and activation. Effort pertains to the energy that is necessary to meet the demands of a specific task and may be affected by cognitive load. Effort is presumed to be required when the current state of an organism does not meet the required state to complete a particular task. During such situations, the allocation of additional attentional resources is needed (Sergeant, 2000). It is plausible that the digit cancellation task used to assess attention did not require the participants to rely sufficiently on the pool of effort.

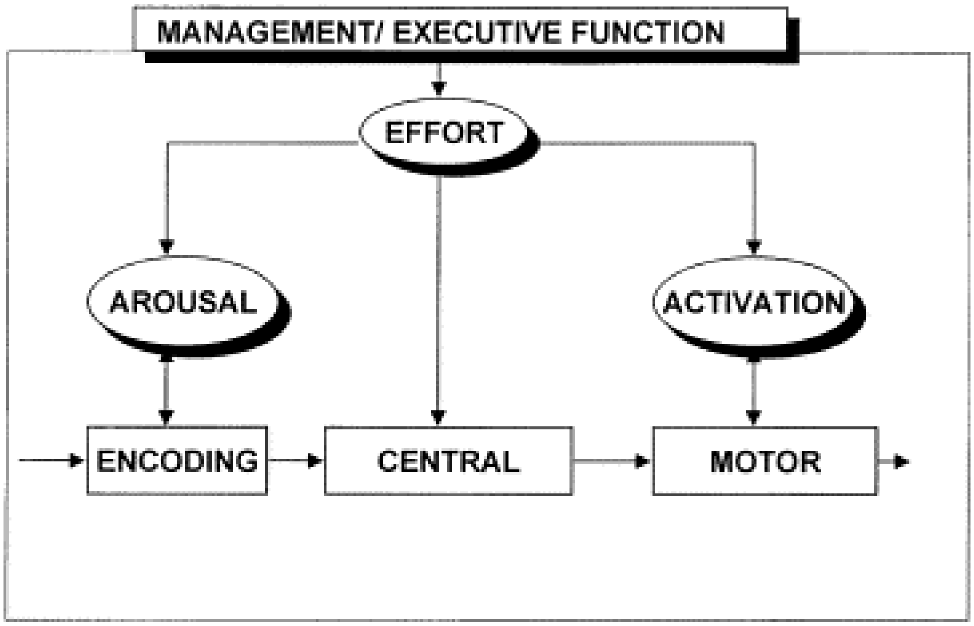


Figure 4.9 – The Cognitive-Energetics Model, from (Sergeant, 2000)

Expanding upon the physical activity-cognition relationship, the hypofrontality theory, which relies primarily on neurophysiological evidence also provides insight into the effects of physical activity on cognitive functioning. Building on the existing fundamental principle that the brain is responsible of a complex higher level of competitive processing, both mental and motor, it has a finite number of resources which it can utilize. The transient hypofrontality hypothesis posits that during physical activity, there is some neural activation required to achieve motor regulation, process sensory inputs, and coordinate autonomic regulation, all which result in the decrease of neural activity in the prefrontal cortex (Dietrich, 2006). The repetitive activation of the prefrontal cortex during physical activity and attentional tasks such as the digit cancellation task could exhaust the finite number of metabolic resources leading to decrements in either or both tasks. This could in part explain the finding that attention did not mediate the relationship between physical activity and memory encoding.

As discussed in Chapter 2, the attentional network theory has identified three brain networks that carry out the attentional functions of alerting, orienting, and executive attention (Posner & Rothbart, 2007). This framework proposes that attention is not a unitary process, rather composed of three distinct systems that work collaboratively to regulate attentional control. The alerting network maintains an optimal level of arousal to adequately respond to incoming external stimuli. The orienting network directs attentional resources to specific objects within the environment which allows individuals to focus on relevant information while excluding irrelevant information. Executive attention manages conflict resolution and the maintenance of attentional control in the presence of distractions. Imaging data also supports the presence of three distinct brain networks, with different brain networks carrying out the function for alerting, orienting, and executive attention. The primary region responsible for alerting functions is the locus coeruleus which releases the norepinephrine to maintain vigilance. The primary regions responsible for orienting function include the superior parietal lobe and superior colliculus. Executive attention predominantly activates the prefrontal cortex and anterior cingulate cortex. Attention and memory, though related, are regulated by different pathways (D'Aurizio et al., 2023). The multidimensionality of the anterior network theory suggests that the pathways that regulate attention are distinct from those that regulate long-term memory. The characteristics of physical activity that improve long-term memory processes may do so independently of impacting attentional networks. Long-term memory processes may also result in activation of distinct brain regions even in the presence of low attentional demands. Even though memory process can impact attentional control and vice versa, they operate via distinct neural circuits. Physical activity has been implicated to improve long-term memory via synaptic plasticity and hippocampal neurogenesis, independent of attentional networks highlighted in the attentional network theory.

Some experiments that have utilized a digit cancellation type task for assessing attention have provided significant findings (Hatta et al., 2012). However, this evidence supporting the physical activity-attention relation is not conclusive. The majority of experiments that have employed the digit cancellation task as a measure of attention have been with special populations, including individuals with Alzheimer's, attention deficit disorders, and traumatic brain injuries. Support for the use of the digit cancellation task among healthy young adults is limited. Only two randomized controlled trials have utilized the digit cancellation task with healthy young adults. In one experiment, the digit cancellation task was used with healthy young adults (approximately 20 years) to assess the effects of cognitive training, in which no significant changes in attention performance were reported (Nouchi et al., 2020). Another trial assessed selective attention among healthy young adults using a cancellation task (Yano & Yasumura, 2021). Collectively, these data provide a task specific explanation with respect to the results of the present experiment. Attention is not a unitary construct. Given its multidimensional makeup, there is consensus among researchers that it can function selectively. It is also possible that the acute physical activity intervention utilized in the present experiment failed to support the hypothesis that attention would mediate the relationship between physical activity and long-term memory. Future trials should implement a similar study design employing a chronic physical activity intervention to assess the mediating effects of attention on long-term memory.

Individual Differences in Attention

Individual differences in attentional processes may address the results of the current experiment. Individual differences in long-term memory ability, general intelligence, age, motivation, and mood can impact attentional outcomes. There is evidence to suggest individual differences in the ability to allocate attention during encoding is important for individual differences in long-term memory. Individual differences in lapses of attention are also indicative of variation in memory performance. Those that experience more fluctuations in attention will likely encode less information than those who can maintain their attention on the relevant task. Given the relation between attention and long-term memory, it is likely that variation in the allocation during encoding and subsequent retrieval is important to consider for individual differences in both attention and long-term memory.

More specifically, both attention and visuospatial memory share similar characteristics. These similarities are evident in brain regions which activate similarly during tasks of attention as well as visuospatial memory. Dual-task experiments indicate with large loads on both attention and visuospatial working memory, there is a considerable interference between the two processes that occurs therefore confirming that both processes rely on the same resources. These findings have important implications for the present experiment in which both attentional processes and visuospatial memory components were assessed. Despite the importance of attention in the physical activity-memory pathway, these individual differences among young adults may compromise the strength of the relationship between attention and long-term memory.

4.5.5 Physical Activity Complexity

The final aim of this experiment was to determine if physical activity complexity would differentially impact memory processes. The results of the experiment supported the hypothesis as participants who completed a complex bout of physical activity experienced the largest mnemonic benefits, showing less free-recall decay compared to the simple and control conditions measured seven days after encoding. The complex physical activity condition included unpredictable movement patterns that required a higher level of cognitive engagement, whereas the simple physical activity condition required predictable movement patterns that did not require a high level of cognitive engagement; the control condition did not require any physical activity. Physical activity type did not significantly impact recognition and object-location memory, suggesting that the impact of physical activity is not universal across long-term memory processes.

These results are in line with existing evidence highlighting the effects of physical activity complexity on long-term memory. Roig and colleagues conducted a series of experiments that focused systematically on variables that moderate the effects of acute bouts of physical activity on procedural learning tasks (Roig et al., 2012). An experiment conducted with preadolescent children showed that acute exercise performed after motor skill learning facilitated long-term motor memory via the promotion of memory consolidation processes (Lundbye-Jensen et al., 2017). Similarly, others (Mang et al., 2016; Skriver et al., 2014) have indicated that acute exercise positively impacted procedural motor memory. Based on theories of memory consolidation discussed in chapter 2 (e.g., McGaugh, 2015), Roig et al. (2016, 2021) proposed that an adequate test for the mnemonic benefits of physical activity entails that sufficient time be provided for processes that underlie encoding, long-term memory storage, and retrieval networks to progress (Taubert et al., 2015). The passage of time transforms labile short-term memories to consolidate into permanent, long-term memory stores. These studies provide important findings that the strength of the mnemonic benefits of acute physical activity is dependent on the temporal relation between a bout of physical activity and encoding.

Recently, researchers have rationalized that the temporal order between physical activity and learning is of relevance to the amount of material that gets encoded. The order of physical activity in relation to encoding has been addressed in detail via several systematic reviews and meta analyses (Loprinzi et al., 2019; Qazi et al., 2024; Roig et al., 2013). The review with meta-analysis by Roig et al. (2013) provides evidence that acute physical activity improves memory in a time-dependent fashion by priming molecular processes that are involved in the encoding, consolidation, and recall of new information. The systematic review with meta-analysis by Loprinzi et al. (2019) focused exclusively on the effects of acute bouts of physical activity on short- and long-term episodic memory with results indicating that physical activity performed prior to and following encoding enhanced performance, with larger effect sizes observed when exercise was performed following encoding than prior to encoding. Qazi et al. (2024) expanded upon the findings of Roig et al. (2013) and Loprinzi et al. (2019) providing further evidence that physical activity prior to encoding improved free-recall memory more, whereas physical activity following encoding improved recognition memory more. In addition to the temporal relationship between physical activity and encoding, the complexity of the physical activity bout has also been identified as an important factor relative to the physical activity-memory relationship.

Recently, researchers have developed interventions that focus specifically on the role of task complexity and mental engagement and its effects on long-term memory processes. Common among these studies is the use and manipulation of physical tasks that involve complex multi-limb sequencing and activation as well as rapid decision-making. Systematically replicating the methodology employed by Roig et al. (2012), Tomporowski and Pendleton (2018) evaluated the effects of a simple or complex 10-minute bout of physical activity compared to resting control on young adult's pursuit-rotor performance. Participants who performed a complex bout of coordinated dance-like movements immediately following the practice of the tracking task demonstrated better retention of time-on-contact than simple repetitive stepping movements, or no physical activity. The findings concluded that complex physical activity resulted in enhanced procedural learning. These results are in line with others who suggest that attention demanding, skill-based physical activity is superior for long-term memory processes compared to repetitive, predicable movements (Merom et al., 2016; Pesce et al., 2009; Roig et al., 2012).

The influence of acute bouts of low-intensity physical activity performed prior to and following the encoding of symbolic information has been explored in a number of experiments. Loprinzi and colleagues explored the effects of acute physical activity on long-term episodic memory. Frith et al. (2017) examined the temporal effects of acute exercise on episodic memory.

Young adults performed a 15-minute bout of acute exercise. Their memory was assessed using the Rey Auditory Verbal Learning Test (RAVLT). The authors concluded that exercise prior to memory encoding was beneficial for long-term memory retention. In another experiment, Sng et al. (2018) also examined the effects of acute, moderate intensity exercise on long-term episodic memory. Young adults completed a 15-mintute bout of exercise and the RAVLT 20 minutes and 24 hours after exercise. Those that completed the exercise bout prior to encoding demonstrated robust long-term memory retention compared those that completed the exercise during the encoding and consolidation periods (Sng et al., 2018). In summary, the results of these experiments and meta-analytic reviews have led to a consensus that brief bouts of low-to-moderate intensity physical activity enhances episodic memory, with the largest effects observed when physical activity precedes encoding.

The mental engagement inherent in cognitively complex bouts of physical activity has been predicted to elevate the effectiveness of single bouts of physical activity on executive functioning and memory. The added benefits of the complexity of physical activity bouts on children’s episodic long-term memory were investigated by Pesce et al. (2009). The authors incorporated a 40-minute intervention including training that included adaptive conditions requiring rapid decisional responses to be made under time constraints. After completing the intervention, children showed improved memory encoding compared to a control condition in which no physical activity was performed (Pesce et al., 2009). The results of Pesce et al. (2009) suggested that an acute bout of physical activity aided memory storage among preadolescent children. The authors concluded that the differential effects of cognitively engaging physical activity were facilitated by cognitive activation induced by activity demands. Similar findings have been obtained and reported in several experiments and reviews. Budde et al. (2008)

employed a 10-minute bout of coordinative physical activity based on soccer training that included the ability of adolescents to balance and adjust to variable conditions. Adolescents who completed the complex movement program performed better on tests of attention and concentration than adolescents who completed a normal physical activity program without increased coordinative demands (Budde et al., 2008). A recent systematic review and meta-analysis reported that cognitively engaging physical activity interventions positively impacted select components of memory and executive function among children and adolescents (Mao et al., 2024).

Issues relating to the quantification of physical activity complexity have been a topic of contention among contemporary researchers. The factors that comprise the complexity of physical activity include gross movements that require limb coordination, executive level movement analyses, and decision making capabilities. Vital components of movement complexity, intralimb and interlimb coordination are both required to maintain functional demands of locomotion and other gross movement actions (Hasan et al., 2016; Reisman et al., 2005). Similarly, complex movement patterns also require the activation of executive level cognitive analyses that require top-down thalamic control to produce goal-directed actions (Makino, 2019). The manipulation of these characteristics signifies how varying levels of cognitive engagement may impact learning. More cognitively engaging movement patterns also amplify neural benefits as they are more attentionally engaging and mentally involved than non-engaging, simple movement patterns (De Bruijn et al., 2020). Encompassing the characteristics of physical activity complexity, the Quadrato Motor Training (QMT) intervention was developed to allow researchers to systematically manipulate the cognitive demands of movement patterns (Ben-Soussan et al., 2015).

QMT is a low-intensity, coordination-demanding form of physical activity that combines physical movements with cognitive engagement. QMT requires balance control, coordinative whole-body movements, increased awareness of the body and its location in space, inhibitive control, and enhanced divided attention to motor responses (Ben-Soussan et al., 2015). The movement patterns that are used during QMT can be customized to require participators to step in appropriate boxes in accordance with externally presented verbal cues. In the present experiment, the movement patterns in the simple and complex physical activity conditions were controlled. The simple condition consisted of stepping consistently from one box to the next in a predictable, clockwise manner. The complex condition consisted of sequential trials that required selecting one of three possible step directions (left/right, forward/backward, or diagonal) in accordance with auditory cues. The simple and complex conditions required participants to select a movement plan, and then inhibit the initiation response until cued to do so, requiring varying levels of cognitive engagement in each condition. It has been hypothesized by Ben-Soussan et al. that cerebellar networks are involved in movement production, control, and coordination of complex movement patterns. QMT interventions have also been shown to improve cognitive function. Planned movement patterns and their execution requiring attention, cognitive flexibility, and molecular alterations are responsible for changes in cognitive function. In summary, the complex condition of the QMT intervention used in the present experiment provided participants with an elevated level of cognitive engagement that resulted in long-term memory changes.

4.6 Limitations and Future Direction

It is acknowledged that there are some limitations to this experiment. Numerous methodological shortcomings were apparent. Though the experiment was designed with this in consideration, the participants performed generally well on cognitive assessments. Therefore, the generalizability of the present experiment across the lifespan is limited to healthy young adults only. A small number of similar trials conducted with middle-aged and older adults suggests that additional empirical evidence is necessary. Other moderators have also been reported via previous reviews to influence the physical activity-memory relationship. With respect to biological sex, females typically tend to outperform males on most memory tasks (Asperholm et al., 2019). Though both males and females were recruited for the current experiment, the analyses did not account for sex differences.

As concluded in chapter 3, the effects of the physical activity on long-term memory are differential. The results of this experiment indicated that participants who completed a complex bout of physical activity evidenced greater free recall performance than those in the simple and control conditions. Physical activity therefore differentially impacted memory processes. These data are also in line with the meta-analytic findings presented in chapter 3 as well as predictions drawn from Adaptive Capacity Model. The Adaptive Capacity Model highlights that the effects of physical activity are not uniform. The model also infers that brain regions may preferentially show exercise-induced neuroplastic effects when cognitive demands and physical activity are linked. The selective impact of physical activity on the brain causes selective changes in neurogenesis, synaptic plasticity, and brain derived neurotrophic levels. A such, future work should consider partialing out the selective effects of physical activity programs on specific cognitive outcomes and brain structures.

Attentional processes were also hypothesized to significantly mediate and explain the relationship between physical activity and long-term memory. However, significance was not reached. The digit cancellation test of attention was used as the attentional task in the present experiment, which is a singular assessment of several attentional components. This test was selected based on its use in previous experiments which evidenced its efficacy. The results of the present experiment may be restricted to the digit cancellation task. In this experiment, alternative tests of attention may have provided significant effects for mediation. It may also be that the sample size in the present experiment was not large enough to qualify for significant mediation. A review by Fritz and Mackinnon (Fritz & MacKinnon, 2007) indicated that the median sample size for over 200 experiments testing mediation was 187. The a priori assumption was that the digit cancellation task was sensitive to physical activity based on previous experiments. It was therefore unexpected that significant mediation was not achieved. Additional research exploring the mediating effects of attention between physical activity and long-term memory are warranted.

A number of future studies may be conducted to elucidate the effects of physical activity during different timepoints relative to encoding. In the present experiment, physical activity occurred prior to encoding. The results were in line with the meta-analytic findings present in chapter 3. Qazi et al. (Qazi et al., 2024) reported that when physical activity occurs prior to encoding, free-recall memory is affected more than recognition memory. When physical activity occurs after encoding, recognition memory is affected more than free-recall. As such, the authors of this experiment would consider a future line of research that further explores the temporal effects of physical activity on long-term episodic memory.

4.7 Conclusion

Based on the results of the current experiment, it appears that a cognitively engaging, complex bout of physical activity after encoding results in more durable free-recall memory. However, neither recognition nor object-location memory are influenced by physical activity.

Attention did not significantly mediate the relationship between physical activity and long-term memory. The results of the experiment suggest that single bouts of cognitively engaging, moderately intense physical activity may facilitate one type of long-term episodic memory: free-recall memory.

4.8 Acknowledgements

The authors of the experiment would like to thank Life University, who in part funded this experiment.

4.9 Conflict of Interest

The authors declare that there is no potential conflict of interest.

References

Abel, M., & Bäuml, K.-H. T. (2019). List-method directed forgetting after prolonged retention interval: Further challenges to contemporary accounts. *Journal of Memory and Language*, *106*, 18–28. https://doi.org/10.1016/j.jml.2019.02.002

Acheson, S. K., Stein, R. M., & Swartzwelder, H. S. (1998). Impairment of Semantic and Figural Memory by Acute Ethanol: Age-Dependent Effects. *Alcoholism: Clinical and Experimental Research*, *22*(7), 1437–1442. https://doi.org/10.1111/j.1530-0277.1998.tb03932.x

Allen, G. (2004). *Human Spatial Memory: Remembering Where*. Lawrence Erlbaum Associates Publishers. https://www.routledge.com/Human-Spatial-Memory-Remembering-Where/Allen/p/book/9780415648394?srsltid=AfmBOopKn26aYUyf3ytP_ckNCT_M8D6Yt3eGtJ4L6QogxM12Mp_Df9YJ

Alvarado Melo, J. E., León Ariza, H. H., & Ladino Marin, E. V. (2024). Physical activity in students and its association with attention: A systematic review. *Retos: Nuevas Tendencias En Educación Física, Deporte y Recreación*, *56*, 834–845.

Atkinson, R. C., & Shiffrin, R. M. (1968). Human memory: A proposed system and its control processes. In *The psychology of learning and motivation: II* (pp. xi, 249–xi, 249). Academic Press. https://doi.org/10.1016/S0079-7421(08)60422-3

Baddeley, A. D., & Hitch, G. (1974). Working Memory. In G. H. Bower (Ed.), *Psychology of Learning and Motivation* (Vol. 8, pp. 47–89). Academic Press. https://doi.org/10.1016/S0079-7421(08)60452-1

Bennett, D. J. (2023). Does perceiving require perceptual experience? *Review of Philosophy and Psychology*, *14*(3), 763–790. https://doi.org/10.1007/s13164-022-00620-6

Ben-Soussan, T. D. (2016). The Quadrato Motor Training model: Implications to the treatment of Alzheimer and Parkinson’s disease. *Frontiers in Human Neuroscience*, *10*. https://doi.org/10.3389/conf.fnhum.2016.220.00030

Ben-Soussan, T. D., Berkovich-Ohana, A., Glicksohn, J., & Goldstein, A. (2014). A suspended act: Increased reflectivity and gender-dependent electrophysiological change following Quadrato Motor Training. *Frontiers in Psychology*, *5*. https://doi.org/10.3389/fpsyg.2014.00055

Ben-Soussan, T. D., Glicksohn, J., & Berkovich-Ohana, A. (2015). From Cerebellar Activation and Connectivity to Cognition: A Review of the Quadrato Motor Training. *BioMed Research International*, *2015*, 954901. https://doi.org/10.1155/2015/954901

Budde, H., Voelcker-Rehage, C., Pietrabyk-Kendziorra, S., Ribeiro, P., & Tidow, G. (2008).

Acute coordinative exercise improves attentional performance in adolescents. *Neuroscience Letters*, *441*(2), 219–223. https://doi.org/10.1016/j.neulet.2008.06.024

Cassilhas, R. C., Lee, K. S., Fernandes, J., Oliveira, M. G. M., Tufik, S., Meeusen, R., & de Mello, M. T. (2012). Spatial memory is improved by aerobic and resistance exercise through divergent molecular mechanisms. *Neuroscience*, *202*, 309–317. https://doi.org/10.1016/j.neuroscience.2011.11.029

Chang, Y. K., Labban, J. D., Gapin, J. I., & Etnier, J. L. (2012). The effects of acute exercise on cognitive performance: A meta-analysis. *Brain Research*, *1453*, 87–101. https://doi.org/10.1016/j.brainres.2012.02.068

Chen, F.-T., Etnier, J. L., Chan, K.-H., Chiu, P.-K., Hung, T.-M., & Chang, Y.-K. (2020). Effects of Exercise Training Interventions on Executive Function in Older Adults: A Systematic Review and Meta-Analysis. *Sports Medicine*, *50*(8), 1451–1467. https://doi.org/10.1007/s40279-020-01292-x

Coles, K., & Tomporowski, P. D. (2008). Effects of acute exercise on executive processing, short-term and long-term memory. *Journal of Sports Sciences*, *26*(3), 333–344. https://doi.org/10.1080/02640410701591417

Conway, B. R. (2018). The Organization and Operation of Inferior Temporal Cortex. *Annual Review of Vision Science*, *4*, 381–402. https://doi.org/10.1146/annurev-vision-091517-034202

Criss, A. H., & Shiffrin, R. M. (20040712). Context Noise and Item Noise Jointly Determine Recognition Memory: A Comment on Dennis and Humphreys (2001). *Psychological Review*, *111*(3), 800. https://doi.org/10.1037/0033-295X.111.3.800

D’Aurizio, G., Festucci, F., Di Pompeo, I., Tempesta, D., & Curcio, G. (2023). Effects of Physical Activity on Cognitive Functioning: The Role of Cognitive Reserve and Active Aging. *Brain Sciences*, *13*(11), Article 11. https://doi.org/10.3390/brainsci13111581

Davey, C. P. (1973). Physical exertion and mental performance. *Ergonomics*, *16*(5), 595–599. https://doi.org/10.1080/00140137308924550

De Bruijn, A. G. M., Kostons, D. D. N. M., Van Der Fels, I. M. J., Visscher, C., Oosterlaan, J., Hartman, E., & Bosker, R. J. (2020). Effects of aerobic and cognitively-engaging physical activity on academic skills: A cluster randomized controlled trial. *Journal of Sports Sciences*, *38*(15), 1806–1817. https://doi.org/10.1080/02640414.2020.1756680

de Greeff, J. W., Bosker, R. J., Oosterlaan, J., Visscher, C., & Hartman, E. (2018). Effects of physical activity on executive functions, attention and academic performance in preadolescent children: A meta-analysis. *Journal of Science and Medicine in Sport*, *21*(5), 501–507. https://doi.org/10.1016/j.jsams.2017.09.595

Dehais, F., Lafont, A., Roy, R., & Fairclough, S. (2020). A Neuroergonomics Approach to Mental Workload, Engagement and Human Performance. *Frontiers in Neuroscience*, *14*. https://doi.org/10.3389/fnins.2020.00268

Diamond, D. M., Campbell, A. M., Park, C. R., Halonen, J., & Zoladz, P. R. (2007). The Temporal Dynamics Model of Emotional Memory Processing: A Synthesis on the Neurobiological Basis of Stress-Induced Amnesia, Flashbulb and Traumatic Memories, and the Yerkes-Dodson Law. *Neural Plasticity*, *2007*, 60803. https://doi.org/10.1155/2007/60803

Dietrich, A. (2006). Transient hypofrontality as a mechanism for the psychological effects of exercise. *Psychiatry Research*, *145*(1), 79–83. https://doi.org/10.1016/j.psychres.2005.07.033

Dulaney, C. L., & Ellis, N. R. (1991). Long-term recognition memory for items and attributes by retarded and nonretarded persons. *Intelligence*, *15*(1), 105–115. https://doi.org/10.1016/0160-2896(91)90024-8

Eichenbaum, H., & Cohen, N. J. (2014). Can we reconcile the declarative memory and spatial navigation views on hippocampal function? *Neuron*, *83*(4), 764–770. https://doi.org/10.1016/j.neuron.2014.07.032

Ellis, N. R., Woodley-Zanthos, P., & Dulaney, C. L. (1989). Memory for spatial location in children, adults, and mentally retarded persons. *American Journal on Mental Retardation*, *93*, 521–526.

Erickson, K. I., Prakash, R. S., Voss, M. W., Chaddock, L., Hu, L., Morris, K. S., White, S. M., Wójcicki, T. R., McAuley, E., & Kramer, A. F. (2009). Aerobic fitness is associated with hippocampal volume in elderly humans. *Hippocampus*, *19*(10), 1030–1039. https://doi.org/10.1002/hipo.20547

Erickson, K. I., Voss, M. W., Prakash, R. S., Basak, C., Szabo, A., Chaddock, L., Kim, J. S., Heo, S., Alves, H., White, S. M., Wojcicki, T. R., Mailey, E., Vieira, V. J., Martin, S. A., Pence, B. D., Woods, J. A., McAuley, E., & Kramer, A. F. (2011). Exercise training increases size of hippocampus and improves memory. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(7), 3017–3022. https://doi.org/10.1073/pnas.1015950108

Fan, J. E., Wammes, J. D., Gunn, J. B., Yamins, D. L. K., Norman, K. A., & Turk-Browne, N. B. (2020). Relating Visual Production and Recognition of Objects in Human Visual Cortex. *Journal of Neuroscience*, *40*(8), 1710–1721. https://doi.org/10.1523/JNEUROSCI.1843-19.2019

Faul, F., Erdfelder, E., Buchner, A., & Lang, A.-G. (2009). Statistical power analyses using G*Power 3.1: Tests for correlation and regression analyses. *Behavior Research Methods*, *41*(4), 1149–1160. https://doi.org/10.3758/BRM.41.4.1149

Fedewa, A., Mayo, M. R., Ahn, S., & Erwin, H. (2021). A School-Based Physical Activity Intervention for Young Children: Are There Effects on Attention and Behavior? *Journal of Applied School Psychology*, *37*(4), 391–414. https://doi.org/10.1080/15377903.2020.1858380

Frith, E., Sng, E., & Loprinzi, P. D. (2017). Randomized controlled trial evaluating the temporal effects of high-intensity exercise on learning, short-term and long-term memory, and prospective memory. *The European Journal of Neuroscience*, *46*(10), 2557–2564. https://doi.org/10.1111/ejn.13719

Godin, G., & Shephard, R. J. (1985). A simple method to assess exercise behavior in the community. *Canadian Journal of Applied Sport Sciences. Journal Canadien Des Sciences Appliquees Au Sport*, *10*(3), 141–146.

Gomes da Silva, S., Unsain, N., Mascó, D. H., Toscano-Silva, M., de Amorim, H. A., Silva Araújo, B. H., Simões, P. S. R., da Graça Naffah-Mazzacoratti, M., Mortara, R. A., Scorza, F. A., Cavalheiro, E. A., & Arida, R. M. (2012). Early exercise promotes positive hippocampal plasticity and improves spatial memory in the adult life of rats. *Hippocampus*, *22*(2), 347–358. https://doi.org/10.1002/hipo.20903

Green, D. M., & Swets, J. A. (1974). *Signal detection theory and psychophysics*. R.E. Krieger Pub. Co.

Hasan, S. M. M., Rancourt, S. N., Austin, M. W., & Ploughman, M. (2016). Defining Optimal Aerobic Exercise Parameters to Affect Complex Motor and Cognitive Outcomes after Stroke: A Systematic Review and Synthesis. *Neural Plasticity*, *2016*(1), 2961573. https://doi.org/10.1155/2016/2961573

Hasher, L., & Zacks, R. T. (1979). Automatic and effortful processes in memory. *Journal of Experimental Psychology: General*, *108*(3), 356–388. https://doi.org/10.1037/0096-3445.108.3.356

Hatta, T., Yoshizaki, K., ITO, Y., MASE, M., & KABASAWA, H. (2012). Reliability and validity of the digit cancellation test, a brief screen of attention. *Psychologia*, *55*, 246–256. https://doi.org/10.2117/psysoc.2012.246

Haverkamp, B. F., Wiersma, R., Vertessen, K., van Ewijk, H., Oosterlaan, J., & Hartman, E. (2020). Effects of physical activity interventions on cognitive outcomes and academic performance in adolescents and young adults: A meta-analysis. *Journal of Sports Sciences*, *38*(23), 2637–2660. https://doi.org/10.1080/02640414.2020.1794763

Hopkins, M. E., Nitecki, R., & Bucci, D. J. (2011). Physical exercise during adolescence versus adulthood: Differential effects on object recognition memory and brain-derived neurotrophic factor levels. *Neuroscience*, *194*, 84–94. https://doi.org/10.1016/j.neuroscience.2011.07.071

Hötting, K., Schickert, N., Kaiser, J., Röder, B., & Schmidt-Kassow, M. (2016). The Effects of Acute Physical Exercise on Memory, Peripheral BDNF, and Cortisol in Young Adults. *Neural Plasticity*, *2016*, 1–12. https://doi.org/10.1155/2016/6860573

Jenkins, J. J. (1979). Four Points to Remember: A Tetrahedral Model of Memory Experiments. In *Levels of Processing in Human Memory (PLE: Memory)*. Psychology Press.

Kao, S.-C., Cadenas-Sanchez, C., Shigeta, T. T., Walk, A. M., Chang, Y.-K., Pontifex, M. B., & Hillman, C. H. (2020). A systematic review of physical activity and cardiorespiratory fitness on P3b. *Psychophysiology*, *57*(7), e13425. https://doi.org/10.1111/psyp.13425

Katz, E. R., & Ellis, N. R. (1991). Memory for spatial location in retarded and nonretarded persons. *Journal of Intellectual Disability Research*, *35*(3), 209–220. https://doi.org/10.1111/j.1365-2788.1991.tb01054.x

Koelega, H. S. (1996). Sustained attention. In O. Neumann & A. F. Sanders (Eds.), *Handbook of Perception and Action* (Vol. 3, pp. 277–331). Academic Press. https://doi.org/10.1016/S1874-5822(96)80025-9

Labban, J. D., & Etnier, J. L. (2011). Effects of acute exercise on long-term memory. *Research Quarterly for Exercise and Sport*, *82*(4), 712–721. https://doi.org/10.1080/02701367.2011.10599808

LaLumiere, R. T., McGaugh, J. L., & McIntyre, C. K. (2017). Emotional Modulation of Learning and Memory: Pharmacological Implications. *Pharmacological Reviews*, *69*(3), 236–255. https://doi.org/10.1124/pr.116.013474

Lambourne, K., & Tomporowski, P. (2010). The effect of exercise-induced arousal on cognitive task performance: A meta-regression analysis. *Brain Research*, *1341*, 12–24. https://doi.org/10.1016/j.brainres.2010.03.091

Lefferts, W. K., DeBlois, J. P., White, C. N., & Heffernan, K. S. (2019). Effects of Acute Aerobic Exercise on Cognition and Constructs of Decision-Making in Adults With and Without Hypertension. *Frontiers in Aging Neuroscience, 11*. https://doi.org/10.3389/fnagi.2019.00041

Lohnas, L. J., Polyn, S. M., & Kahana, M. J. (2011). Contextual Variability in Free Recall. *Journal of Memory and Language*, *64*(3), 249–255. https://doi.org/10.1016/j.jml.2010.11.003

Loprinzi, P. D., Blough, J., Crawford, L., Ryu, S., Zou, L., & Li, H. (2019). The Temporal Effects of Acute Exercise on Episodic Memory Function: Systematic Review with Meta-Analysis. *Brain Sciences*, *9*(4), E87. https://doi.org/10.3390/brainsci9040087

Loprinzi, P. D., Roig, M., Etnier, J. L., Tomporowski, P. D., & Voss, M. (2021). Acute and Chronic Exercise Effects on Human Memory: What We Know and Where to Go from Here. *Journal of Clinical Medicine*, *10*(21), 4812. https://doi.org/10.3390/jcm10214812

Lundbye-Jensen, J., Skriver, K., Nielsen, J. B., & Roig, M. (2017). Acute Exercise Improves Motor Memory Consolidation in Preadolescent Children. *Frontiers in Human Neuroscience*, *11*, 182. https://doi.org/10.3389/fnhum.2017.00182

Macmillan, N. A., & Creelman, C. D. (2004). *Detection Theory: A User's Guide* (2nd ed.). Psychology Press. https://doi.org/10.4324/9781410611147

Makino, H. (2019). Top-down control: A unified principle of cortical learning. *Neuroscience Research*, *141*, 23–28. https://doi.org/10.1016/j.neures.2018.08.004

Malmberg, K. J., Raaijmakers, J. G. W., & Shiffrin, R. M. (2019). 50 years of research sparked by Atkinson and Shiffrin (1968). *Memory & Cognition*, *47*(4), 561–574. https://doi.org/10.3758/s13421-019-00896-7

Mang, C. S., Snow, N. J., Wadden, K. P., Campbell, K. L., & Boyd, L. A. (2016). High-Intensity Aerobic Exercise Enhances Motor Memory Retrieval. *Medicine and Science in Sports and Exercise*, *48*(12), 2477–2486. https://doi.org/10.1249/MSS.0000000000001040

Mao, F., Huang, F., Zhao, S., & Fang, Q. (2024). Effects of cognitively engaging physical activity interventions on executive function in children and adolescents: A systematic review and meta-analysis. *Frontiers in Psychology*, *15*. https://doi.org/10.3389/fpsyg.2024.1454447

McAuley, E., Duncan, T., & Tammen, V. V. (1989). Psychometric properties of the Intrinsic Motivation Inventory in a competitive sport setting: A confirmatory factor analysis. *Research Quarterly for Exercise and Sport*, *60*(1), 48–58. https://doi.org/10.1080/02701367.1989.10607413

McGaugh, J. L. (2004). The amygdala modulates the consolidation of memories of emotionally arousing experiences. *Annual Review of Neuroscience*, *27*, 1–28. https://doi.org/10.1146/annurev.neuro.27.070203.144157

McGaugh, J. L. (2013). Making lasting memories: Remembering the significant. *Proceedings of the National Academy of Sciences of the United States of America*, *110*(Suppl 2), 10402–10407. https://doi.org/10.1073/pnas.1301209110

McGaugh, J. L. (2015). Consolidating Memories. *Annual Review of Psychology*, *66*(1), 1–24. https://doi.org/10.1146/annurev-psych-010814-014954

McMorris, T. (2016a). Developing the catecholamines hypothesis for the acute exercise-cognition interaction in humans: Lessons from animal studies. *Physiology & Behavior*, *165*, 291–299. https://doi.org/10.1016/j.physbeh.2016.08.011

McMorris, T. (2016b). Reappraisal of the acute, moderate intensity exercise-catecholamines interaction effect on speed of cognition: Role of the vagal/NTS afferent pathway. *Journal of Applied Physiology (Bethesda, Md.: 1985)*, *120*(6), 657–658. https://doi.org/10.1152/japplphysiol.00749.2015

McMorris, T. (2021). The acute exercise-cognition interaction: From the catecholamines hypothesis to an interoception model. *International Journal of Psychophysiology*, *170*, 75–88. https://doi.org/10.1016/j.ijpsycho.2021.10.005

Merom, D., Grunseit, A., Eramudugolla, R., Jefferis, B., Mcneill, J., & Anstey, K. J. (2016). Cognitive Benefits of Social Dancing and Walking in Old Age: The Dancing Mind Randomized Controlled Trial. *Frontiers in Aging Neuroscience*, *8*, 26. https://doi.org/10.3389/fnagi.2016.00026

Milner, A., & Goodale, M. (1997). The Visual Brain in Action. *Optometry and Vision Science – OPTOMETRY VISION SCI*, *74*. https://doi.org/10.1093/acprof:oso/9780198524724.001.0001
Muthén, L. K., & Muthén, B. O. (1998). *Mplus user's guide (7th ed.)*.

Nielson, K. A., Radtke, R. C., & Jensen, R. A. (1996). Arousal-Induced Modulation of Memory Storage Processes in Humans. *Neurobiology of Learning and Memory*, *66*(2), 133–142. https://doi.org/10.1006/nlme.1996.0054

Nouchi, R., Kawata, N. Y. dos S., Saito, T., Himmelmeier, R. M., Nakamura, R., Nouchi, H., & Kawashima, R. (2020). Dorsolateral Prefrontal Cortex Activity during a Brain Training Game Predicts Cognitive Improvements after Four Weeks' Brain Training Game Intervention: Evidence from a Randomized Controlled Trial. *Brain Sciences*, *10*(8), Article 8. https://doi.org/10.3390/brainsci10080560

Nuzum, H., Stickel, A., Corona, M., Zeller, M., Melrose, R. J., & Wilkins, S. S. (2020). Potential Benefits of Physical Activity in MCI and Dementia. *Behavioural Neurology*, *2020*, 7807856. https://doi.org/10.1155/2020/7807856

Pesce, C., Crova, C., Cereatti, L., Casella, R., & Bellucci, M. (2009b). Physical activity and mental performance in preadolescents: Effects of acute exercise on free-recall memory. *Mental Health and Physical Activity*, *2*, 16–22. https://doi.org/10.1016/j.mhpa.2009.02.001

Pontifex, M. B., McGowan, A. L., Chandler, M. C., Gwizdala, K. L., Parks, A. C., Fenn, K., & Kamijo, K. (2019). A primer on investigating the after effects of acute bouts of physical activity on cognition. *Psychology of Sport and Exercise*, *40*, 1–22. https://doi.org/10.1016/j.psychsport.2018.08.015

Posner, M. I., & Rothbart, M. K. (2007). Research on attention networks as a model for the integration of psychological science. *Annual Review of Psychology*, *58*, 1–23. https://doi.org/10.1146/annurev.psych.58.110405.085516

Qazi, A. S., Schmid, D., Gridley, N., Lambourne, K., Daly-Smith, A. J., & Tomporowski, P. D. (2024). The effects of acute exercise on long-term episodic memory: A systematic review and meta-analysis. *Frontiers in Cognition*, *3*. https://doi.org/10.3389/fcogn.2024.1367569

Raichlen, D. A., & Alexander, G. E. (2017). Adaptive Capacity: An evolutionary-neuroscience model linking exercise, cognition, and brain health. *Trends in Neurosciences*, *40*(7), 408. https://doi.org/10.1016/j.tins.2017.05.001

Ramirez Butavand, D., Rodriguez, M. F., Cifuentes, M. V., Miranda, M., Bauza, C. G., Bekinschtein, P., & Ballarini, F. (2023). Acute and chronic physical activity improves spatial memory in an immersive virtual reality task. *iScience*, *26*(3), 106176. https://doi.org/10.1016/j.isci.2023.106176

Reisman, D. S., Block, H. J., & Bastian, A. J. (2005). Interlimb Coordination During Locomotion: What Can be Adapted and Stored? *Journal of Neurophysiology*, *94*(4), 2403–2415. https://doi.org/10.1152/jn.00089.2005

Richards, J., Chohan, A., & Erande, R. (2013). Chapter 15—Biomechanics. In S. B. Porter (Ed.), *Tidy's Physiotherapy (Fifteenth Edition)* (pp. 331–368). Churchill Livingstone. https://doi.org/10.1016/B978-0-7020-4344-4.00015-8

Robison, M. K., & Brewer, G. A. (2020). Individual differences in working memory capacity and the regulation of arousal. *Attention, Perception, & Psychophysics*, *82*(7), 3273–3290. https://doi.org/10.3758/s13414-020-02077-0

Roig, M., Nordbrandt, S., Geertsen, S. S., & Nielsen, J. B. (2013). The effects of cardiovascular exercise on human memory: A review with meta-analysis. *Neuroscience and Biobehavioral Reviews*, *37*(8), 1645–1666. https://doi.org/10.1016/j.neubiorev.2013.06.012

Roig, M., Skriver, K., Lundbye-Jensen, J., Kiens, B., & Nielsen, J. B. (2012). A single bout of exercise improves motor memory. *PloS One*, *7*(9), e44594. https://doi.org/10.1371/journal.pone.0044594

Roig, M., Thomas, R., Mang, C. S., Snow, N. J., Ostadan, F., Boyd, L. A., & Lundbye-Jensen, J. (2016). Time-Dependent Effects of Cardiovascular Exercise on Memory. *Exercise and Sport Sciences Reviews*, *44*(2), 81–88. https://doi.org/10.1249/JES.0000000000000078

Roozendaal, B., & Hermans, E. J. (2017). Norepinephrine effects on the encoding and consolidation of emotional memory: Improving synergy between animal and human studies. *Current Opinion in Behavioral Sciences*, *14*, 115–122. https://doi.org/10.1016/j.cobeha.2017.02.001

Ryan, R. M. (n.d.). *Control and Information in the Intrapersonal Sphere: An Extension of Cognitive Evaluation Theory*. 12.

Segal, S. K., Cotman, C. W., & Cahill, L. F. (2012). Exercise-Induced Noradrenergic Activation Enhances Memory Consolidation in Both Normal Aging and Patients with Amnestic Mild Cognitive Impairment. *Journal of Alzheimer's Disease*, *32*(4), 1011–1018. https://doi.org/10.3233/JAD-2012-121078

Sergeant, J. (2000). The cognitive-energetic model: An empirical approach to Attention-Deficit Hyperactivity Disorder. *Neuroscience & Biobehavioral Reviews*, *24*(1), 7–12. https://doi.org/10.1016/S0149-7634(99)00060-3

Shih, P.-C., Yang, Y.-R., & Wang, R.-Y. (2013). Effects of Exercise Intensity on Spatial Memory Performance and Hippocampal Synaptic Plasticity in Transient Brain Ischemic Rats. *PLOS ONE*, *8*(10), e78163. https://doi.org/10.1371/journal.pone.0078163

Skriver, K., Roig, M., Lundbye-Jensen, J., Pingel, J., Helge, J. W., Kiens, B., & Nielsen, J. B. (2014). Acute exercise improves motor memory: Exploring potential biomarkers. *Neurobiology of Learning and Memory*, *116*, 46–58. https://doi.org/10.1016/j.nlm.2014.08.004

Sng, E., Frith, E., & Loprinzi, P. D. (2018). Temporal Effects of Acute Walking Exercise on Learning and Memory Function. *American Journal of Health Promotion: AJHP*, *32*(7), 1518–1525. https://doi.org/10.1177/0890117117749476

Szekely, A., Jacobsen, T., D'Amico, S., Devescovi, A., Andonova, E., Herron, D., Lu, C. C., Pechmann, T., Pléh, C., Wicha, N., Federmeier, K., Gerdjikova, I., Gutierrez, G., Hung, D., Hsu, J., Iyer, G., Kohnert, K., Mehotcheva, T., Orozco-Figueroa, A., … Bates, E. (2004). A new on-line resource for psycholinguistic studies. *Journal of Memory and Language*, *51*(2), 247–250.

Taubert, M., Draganski, B., Anwander, A., Mueller, K., Horstmann, A., Villringer, A., & Ragert, P. (2010). Dynamic Properties of Human Brain Structure: Learning-Related Changes in Cortical Areas and Associated Fiber Connections. *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience*, *30*, 11670–11677. https://doi.org/10.1523/JNEUROSCI.2567-10.2010

Tomporowski, P. D., Ellis, N. R., & Stephens, R. (1987). The immediate effects of strenuous exercise on free-recall memory. *Ergonomics*, *30*(1), 121–129. https://doi.org/10.1080/00140138708969682

Tomporowski, P. D., McCullick, B., Pendleton, D. M., & Pesce, C. (2015). Exercise and children's cognition: The role of exercise characteristics and a place for metacognition. *Journal of Sport and Health Science*, *4*(1), 47–55. https://doi.org/10.1016/j.jshs.2014.09.003

Tomporowski, P. D., & Pendleton, D. M. (2018). Effects of the Timing of Acute Exercise and Movement Complexity on Young Adults' Psychomotor Learning. *Journal of Sport and Exercise Psychology*, *40*(5), 240–248. https://doi.org/10.1123/jsep.2017-0289

Tudor-Locke, C., Mora-Gonzalez, J., Ducharme, S. W., Aguiar, E. J., Schuna, J. M., Barreira, T. V., Moore, C. C., Chase, C. J., Gould, Z. R., Amalbert-Birriel, M. A., Chipkin, S. R., & Staudenmayer, J. (2021). Walking cadence (steps/min) and intensity in 61–85-year-old adults: The CADENCE-Adults study. *The International Journal of Behavioral Nutrition and Physical Activity*, *18*, 129. https://doi.org/10.1186/s12966-021-01199-4

Unsworth, N. (2019). Individual differences in long-term memory. *Psychological Bulletin*, *145*(1), 79–139. https://doi.org/10.1037/bul0000176

Uysal, N., Tugyan, K., Kayatekin, B. M., Acikgoz, O., Bagriyanik, H. A., Gonenc, S., Ozdemir, D., Aksu, I., Topcu, A., & Semin, I. (2005). The effects of regular aerobic exercise in adolescent period on hippocampal neuron density, apoptosis and spatial memory. *Neuroscience Letters*, *383*(3), 241–245. https://doi.org/10.1016/j.neulet.2005.04.054

van Asselen, M., Kessels, R. P. C., Frijns, C. J. M., Jaap Kappelle, L., Neggers, S. F. W., & Postma, A. (2009). Object-location memory: A lesion-behavior mapping study in stroke patients. *Brain and Cognition*, *71*(3), 287–294. https://doi.org/10.1016/j.bandc.2009.07.012

Venezia, A. C., Weiss, L. R., Nielson, K. A., & Smith, J. C. (2023). Moderate-to-vigorous intensity cycling exercise immediately after visual learning enhances delayed recognition memory performance. *Psychology of Sport and Exercise*, *69*, 102498. https://doi.org/10.1016/j.psychsport.2023.102498

Vogel-Ciernia, A., & Wood, M. A. (2014). Examining Object Location and Object Recognition Memory in Mice. *Current Protocols in Neuroscience / Editorial Board, Jacqueline N. Crawley ... [et Al.]*, *69*, 8.31.1-8.31.17. https://doi.org/10.1002/0471142301.ns0831s69

Weinberg, L., Hasni, A., Shinohara, M., & Duarte, A. (2014). A single bout of resistance exercise can enhance episodic memory performance. *Acta Psychologica*, *153*, 13–19. https://doi.org/10.1016/j.actpsy.2014.06.011

Wixted, J. T. (2007). Dual-process theory and signal-detection theory of recognition memory. *Psychological Review*, *114*(1), 152–176. https://doi.org/10.1037/0033-295X.114.1.152 Yano, K., & Yasumura, A. (2021). Brain activity in the prefrontal cortex during a cancellation task: Effects of the target-to-distractor ratio. *Experimental Brain Research*, *239*(9), 2851–2858. https://doi.org/10.1007/s00221-021-06177-7

Yonelinas, A. P., Ranganath, C., Ekstrom, A. D., & Wiltgen, B. J. (2019). A contextual binding theory of episodic memory: Systems consolidation reconsidered. *Nature Reviews Neuroscience*, *20*(6), Article 6. https://doi.org/10.1038/s41583-019-0150-4

Taubert, M., Draganski, B., Anwander, A., Mueller, K., Horstmann, A., Villringer, A., & Ragert, P. (2010). Dynamic Properties of Human Brain Structure: Learning-Related Changes in Cortical Areas and Associated Fiber Connections. *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience*, *30*, 11670–11677. https://doi.org/10.1523/JNEUROSCI.2567-10.2010

Tomporowski, P. D., & Pendleton, D. M. (2018). Effects of the Timing of Acute Exercise and Movement Complexity on Young Adults' Psychomotor Learning. *Journal of Sport and Exercise Psychology*, *40*(5), 240–248. https://doi.org/10.1123/jsep.2017-0289

CHAPTER 5

CONCLUSION

This dissertation aimed to assess the effects of an acute bout of physical activity on young adults' long-term episodic memory processes. There has been a growing interest in in the effects of acute physical activity on different populations (Chaddock-Heyman et al., 2014; de Greeff et al., 2018a; Khan & Hillman, 2014; Ludyga et al., 2016). However, recent evidence suggests that physical activity may have differential effects on memory processes (Qazi et al., 2024). Additionally, the temporal context in which the bout of physical activity occurs could also impact how much information is learned (Roig et al., 2013). Yet to be addressed are questions concerning the uniformity of acute exercise effects across different forms of memory. The components of memory can be segregated and studied individually to provide a clear explanation of its exact mechanisms. There has also been a lack of evidence that incorporates the role of attention between physical activity and long-term episodic memory. With the lack of evidence that exists to answer these inquires, a a systematic review with meta-analysis was designed and aimed at identifying and summarizing current research evidence that has been conducted with acute bouts of physical activity and long-term memory. Informed by the results of the meta-analysis presented in chapter 3, an experiment was conducted to answer the specific effects of physical activity on free-recall, recognition, and object-location memory processes. The outcome measures of the experiment were long-term retention of free-recall, recognition, and object-location memory.

The results of the meta-analysis revealed that acute bouts of physical activity performed prior to, following, and during encoding have selective effects on free-recall and recognition memory. This review of the relevant literature clarifies the benefits of properly placed acute physical activity bouts on adults' episodic memory and learning. Though previous reviews have suggested that importance of acute physical activity on long-term retention (Loprinzi et al., 2019; Roig et al., 2013a), no previous evidence has summarized the effects of acute physical activity on different types of memory processes. Given the results of the systematic review with meta-analysis (chapter 3), an experiment was designed to further explore the effects of acute physical activity on young adults' long-term memory. This experiment also explored the potential mediating effect of attention between physical activity and long-term memory.

In summary, the effects of physical activity prior to encoding on long-term memory outcomes were assessed. We recognize that additional research is needed to further study the effects of physical activity that occurs after encoding on long-term memory. The meta-analytic findings presented in chapter 3 also informed us in making predictions relative to the experiment conducted in chapter 4. An outstanding question that we aimed to answer via this dissertation was how an acute bout of physical activity would influence the long-term memory processes of free-recall, recognition, and object location. We also sought to explore the impact of physical activity complexity on long-term memory. Based on our previous work, we considered the temporal relationship between physical activity and encoding as well. One experiment was conducted to partly answer our inquiry, such that a complex bout of physical activity prior to encoding significantly influenced free-recall memory. We recognize that future experiments are needed to assess the impact of physical activity after encoding on long-term memory. In the future, we would like to establish a line of research that expands upon the findings of this dissertation. We also aim to further assess the temporal relationship between acute physical activity and long-term memory. Additionally, we would like to continue to assess the mediational effect of attentional process between physical activity and long-term memory by utilizing different attentional assessments.

The findings of this dissertation provide several important practical considerations. Because the effects of physical activity on long-term memory are not uniform, teachers, educators, and practitioners should carefully develop movement-based interventions to maximize learning at different age groups. Based on the results of this dissertation and in accordance with previous data, we also propose that physical activity has selective effects on different brain regions. This has strong implications for clinical populations as well. Physical activity programs can be designed and implemented as therapeutic interventions to target specific brain regions among adults with cognitive impairment. In line with the adaptive capacity model (Raichlen & Alexander, 2017), the results of this dissertation provide further evidence that the effects of cognitively engaging physical activity provide enhanced benefits for brain health. These types of cognitively challenging bouts of physical activity have also been implicated for the maintenance of brain health across the lifespan. With respect to cognition, not all components of long-term memory will be influenced by the complexity of physical activity. These changes are related to the development of brain structures over the millennia. Therefore, it is expected that the complexity physical activity based on mental engagement has selective effects on memory processes. The evolution of our species has led to structural and molecular changes in the brain that have proven vital to our survival. Additional neuropsychological and behavioral research is needed to develop a clearer understanding of the exact mechanism by which physical activity influences specific brain structures.

In conclusion, acute physical activity that occurs prior to encoding influences free-recall memory process more than recognition. Physical activity that occurs after encoding influences recognition memory more than free-recall. Additionally, a complex bout of physical activity results in better free-recall memory compared to recognition and object-location memory.

References

Chaddock-Heyman, L., Hillman, C. H., Cohen, N. J., & Kramer, A. F. (2014). III. The importance of physical activity and aerobic fitness for cognitive control and memory in children. *Monographs of the Society for Research in Child Development*, *79*(4), 25–50. https://doi.org/10.1111/mono.12129

Chen, F.-T., Etnier, J. L., Chan, K.-H., Chiu, P.-K., Hung, T.-M., & Chang, Y.-K. (2020). Effects of Exercise Training Interventions on Executive Function in Older Adults: A Systematic Review and Meta-Analysis. *Sports Medicine*, *50*(8), 1451–1467. https://doi.org/10.1007/s40279-020-01292-x

Cox, E. P., O'Dwyer, N., Cook, R., Vetter, M., Cheng, H. L., Rooney, K., & O'Connor, H. (2016). Relationship between physical activity and cognitive function in apparently healthy young to middle-aged adults: A systematic review. *Journal of Science and Medicine in Sport*, *19*(8), 616–628. https://doi.org/10.1016/j.jsams.2015.09.003

de Greeff, J. W., Bosker, R. J., Oosterlaan, J., Visscher, C., & Hartman, E. (2018). Effects of physical activity on executive functions, attention and academic performance in preadolescent children: A meta-analysis. *Journal of Science and Medicine in Sport*, *21*(5), 501–507. https://doi.org/10.1016/j.jsams.2017.09.595

Esteban-Cornejo, I., Tejero-Gonzalez, C. M., Sallis, J. F., & Veiga, O. L. (2015). Physical activity and cognition in adolescents: A systematic review. *Journal of Science and Medicine in Sport*, *18*(5), 534–539. https://doi.org/10.1016/j.jsams.2014.07.007

Etnier, J. L., Drollette, E. S., & Slutsky, A. B. (2019). Physical activity and cognition: A narrative review of the evidence for older adults. *Psychology of Sport and Exercise*, *42*, 156–166. https://doi.org/10.1016/j.psychsport.2018.12.006

Khan, N. A., & Hillman, C. H. (2014). The relation of childhood physical activity and aerobic fitness to brain function and cognition: A review. *Pediatric Exercise Science*, *26*(2), 138–146. https://doi.org/10.1123/pes.2013-0125

Li, J. W., O'Connor, H., O'Dwyer, N., & Orr, R. (2017). The effect of acute and chronic exercise on cognitive function and academic performance in adolescents: A systematic review. *Journal of Science and Medicine in Sport*, *20*(9), 841–848. https://doi.org/10.1016/j.jsams.2016.11.025

Ludyga, S., Gerber, M., Brand, S., Holsboer-Trachsler, E., & Pühse, U. (2016). Acute effects of moderate aerobic exercise on specific aspects of executive function in different age and fitness groups: A meta-analysis. *Psychophysiology*, *53*(11), 1611–1626. https://doi.org/10.1111/psyp.12736

Northey, J. M., Cherbuin, N., Pumpa, K. L., Smee, D. J., & Rattray, B. (2018). Exercise interventions for cognitive function in adults older than 50: A systematic review with meta-analysis. *British Journal of Sports Medicine*, *52*(3), 154–160. https://doi.org/10.1136/bjsports-2016-096587

Qazi, A. S., Schmid, D., Gridley, N., Lambourne, K., Daly-Smith, A. J., & Tomporowski, P. D. (2024). The effects of acute exercise on long-term episodic memory: A systematic review and meta-analysis. *Frontiers in Cognition*, *3*. https://doi.org/10.3389/fcogn.2024.1367569

Roig, M., Nordbrandt, S., Geertsen, S. S., & Nielsen, J. B. (2013). The effects of cardiovascular exercise on human memory: A review with meta-analysis. *Neuroscience and Biobehavioral Reviews*, *37*(8), 1645–1666. https://doi.org/10.1016/j.neubiorev.2013.06.012

Verburgh, L., Königs, M., Scherder, E. J. A., & Oosterlaan, J. (2014). Physical exercise and executive functions in preadolescent children, adolescents and young adults: A meta-analysis. *British Journal of Sports Medicine*, *48*(12), 973–979. https://doi.org/10.1136/bjsports-2012-091441

APPENDICES

APPENDIX A

Recruitment Script

We are conducting a laboratory experiment that examines the effects of physical activity on memory, attention, and learning. We seek men and women between the ages of 18-30 years. Participants will be asked to complete three laboratory sessions over a 7-day period in the Cognition and Skill Acquisition Laboratory (221 Ramsey). The first session will require approximately 90 minutes of your time; each of the remaining sessions will require about 20 minutes of your time. Exclusion criteria include: Cardiovascular, neuromuscular, musculoskeletal, or rheumatoid disorders; use of major psychoactive medication (e.g., anti-depressants); movement disorders; diagnosis of memory or learning disorder; neurologic or balance disorder; and English as a second language.

If you would like more information and are interested in volunteering as a research participant, please contact Ahmed Qazi (ahmedqazi@uga.edu).

Principle Investigator: Phillip D. Tomporowski, Ph.D - Department of Kinesiology

APPENDIX B

Consent Form

UNIVERSITY OF GEORGIA
CONSENT FORM
The Effects of an Acute Bout of Physical Activity on Young Adults' Attention, Episodic, and Object Location Memory

You are being asked to take part in a research study. The information in this form will help you decide if you want to be in the study. Please ask the researcher(s) below if there is anything that is not clear or if you need more information.

Principal Investigator: *Phillip Tomporowski*
Department of Kinesiology
ptomporo@uga.edu

Co-Investigator: *Ahmed Qazi*
Department of Kinesiology
ahmedqazi@uga.edu

We are doing this research study to learn more about the effects of physical activity on memory and attention.

You are being invited to be in this research study because you are between 18 - 30 years old and do not have a history of any of the following: 1) cardiovascular, neuromuscular, musculoskeletal, or rheumatoid disorders, 2) use of major psychoactive medication (e.g., anti-depressants, Adderall) within the past 12 months, 3) movement disorders within the past 12 months, 4) diagnosis of memory or learning disorder, 5) neurologic or balance disorders, and 6) you consider English as your first language.

If you agree to participate in this study:

- You will complete a total of 3 sessions over a period of 7 days: the first session lasting no longer than 90 minutes and the remaining sessions lasting about 15 minutes each.

- During laboratory session #1, you will be asked to do the following things:
    - Answer questions about your health and physical activity, which will take about 10 minutes.
    - Have your height and weight measured, which will take about 5 minutes

  - Put on a heart rate monitor and specialized slippers, perform a warm-up on a treadmill, receive training on a stepping physical activity protocol, and an effort scale, which will take about 30 minutes.
  - During the physical activity protocol, a camera will record your movement patterns from behind.
  - Perform an attention task, which will take about 5 minutes.
  - Perform a long-term memory task and an interest questionnaire, which will take about 40 minutes.

- During laboratory session #2 and #3, you will be asked to do the following things.
  - Answer questions about your health and physical activity over the past 24 hours, which will take about 10 minutes.
  - Perform a long-term memory task, which will take about 20 minutes.

- At the end of each session, audio recordings of your free-recall memory responses will be used to verify researcher's accuracy of manually recorded responses. At the end of each session, these audio recordings will be deleted immediately following verification of your responses.

- A camera will be used to record your movements during the physical activity stepping protocol from the back and knees down, so that nothing can be used to identify you. At the conclusion of the data collection period, these videos will be deleted once all of the necessary data has been extracted.

You will receive $10 per hour for their participation in this study, for a total of $20. Upon completion of the study, you will sign a log that is separate from research data indicating that you have received the incentive.

This research involves the transmission of data over the Internet. Every reasonable effort has been taken to ensure the effective use of available technology; however, confidentiality during online communication cannot be guaranteed.

Your participation in this study is voluntary. Refusal to participate will involve no penalty or loss of benefits to which you are otherwise entitled, and you may discontinue participation at any time. Your decision to participate will have no impact on your participation in other academic programs. If you are a current student in any class instructed by Dr. Tomporowski or Mr. Ahmed Qazi, your decision whether or not to participate will not affect grades or class standing, as described in the class syllabus.

You may experience slight muscle discomfort or a slight risk for balance problems such as falling or slipping when walking on the treadmill or performing the stepping protocol. The possibility of soreness is no more than the soreness associated with ballroom dancing. A trained research assistant will be present at all times as a safety measure.

We will take steps to protect your privacy, but there is a small risk that your information could be accidentally disclosed to people not connected to the research. To reduce this risk, your consent form and all data forms will be placed in a locked filing cabinet and only accessible by research personnel. Individuals with access to identifiable information will be limited to the principal investigator and the research personnel supervised by Dr. Tomporowski. We will only keep de-identified data from this research study in the case that it may be used for future research purposes. The code key that links your name to your data will be destroyed at the time of termination of the project (the exact date to be determined by the university IRB).

If you decide to withdraw from the study or the investigator terminates your participation, the information that can be identified as yours will be kept as part of the study and may continue to be analyzed, unless you make a written request to remove, return, or destroy that information.

Any new findings during the research study that may related to your willingness to continue in the study will be provided to you.

No information about you, or provided by you during the research, will be shared with others without your written permission, except if it is necessary to protect your welfare (for example, if you were injured and need physician care) or if required by law. Any information collected during this study will not be used or distributed for future research.

60 participants will take part in the study.

Please feel free to ask questions about this research at any time. You can contact the Principal Investigator, Dr. Tomporowski at 706-542-4183 or ptomporo@uga.edu. If you have any complaints or questions about your rights as a research volunteer, contact the IRB at 706-542-3199 or by email at IRB@uga.edu.

If you agree to participate in this research study, please sign below:

_______________________	______________________	________
Name of Researcher	Signature	Date
_______________________	______________________	_________
Name of Participant	Signature	Date

Please keep one copy and return the signed copy to the researcher.

APPENDIX C

Interest Questionnaire

Participant ID: __________ Date: __________ Time: __________ Group: __________

General Interest Questionnaire You will be asked to answer questions about your interest in the activities you just completed. For each statement, indicate as best you can which answer fits you best.

1. How interested were you in the physical activity task that you just completed?

   1 (Not at all)
   2
   3
   4
   5
   6 (Very)

2. How interested are you in being or becoming a person interested in the physical activity task?

   1 (Not at all)
   2
   3
   4
   5
   6 (Very)

3. I think the physical activity task is very interesting.

   1 (Not true at all)
   2
   3
   4
   5
   6 (Very true)

4. How interested were you in the memory task that you just completed?

   1 (Not at all)
   2
   3

4
5
6 (Very)

5. How interested are you in being or becoming a person interested in the memory task?

1 (Not at all)
2
3
4
5
6 (Very)

6. I think the memory task is very interesting.

1 (Not true at all)
2
3
4
5
6 (Very true)

APPENDIX D

Mplus code for data analysis

```
DATA:
FILE = Data for Mplus.txt;

VARIABLE:
NAMES = Condition TP OR RR FR RECOG OLM;
Missing = all(999);
USEVAR = Condition tp FR;
MODEL:
FR ON tp Condition;
tp on Condition;
Condition;
Model Indirect:
FR IND Condition;

VARIABLE:
NAMES = Condition TP OR RR FR RECOG OLM;
Missing = all(999);
USEVAR = Condition OR FR;
MODEL:
FR ON OR Condition;
OR on Condition;
Condition;
Model Indirect:
FR IND Condition;

VARIABLE:
NAMES = Condition TP OR RR FR RECOG OLM;
Missing = all(999);
USEVAR = Condition rR FR;
MODEL:
FR ON rR Condition;
rR on Condition;
Condition;
Model Indirect:
FR IND Condition;
```

```
VARIABLE:
NAMES = Condition TP OR RR FR RECOG OLM;
Missing = all(999);
USEVAR = Condition tp Recog;
MODEL:
Recog ON tp Condition;
tp on Condition;
Condition;
Model Indirect:
Recog IND Condition;

VARIABLE:
NAMES = Condition TP OR RR FR RECOG OLM;
Missing = all(999);
USEVAR = Condition OR Recog;
MODEL:
Recog ON OR Condition;
OR on Condition;
Condition;
Model Indirect:
Recog IND Condition;

VARIABLE:
NAMES = Condition TP OR RR FR RECOG OLM;
Missing = all(999);
USEVAR = Condition rR Recog;
MODEL:
Recog ON rR Condition;
rR on Condition;
Condition;
Model Indirect:
Recog IND Condition;

VARIABLE:
NAMES = Condition TP OR RR FR RECOG OLM;
Missing = all(999);
USEVAR = Condition tp olm;
MODEL:
olm ON tp Condition;
tp on Condition;
Condition;
Model Indirect:
olm IND Condition;

VARIABLE:
NAMES = Condition TP OR RR FR RECOG OLM;
```

```
Missing = all(999);
USEVAR = Condition OR olm;
MODEL:
olm ON OR Condition;
OR on Condition;
Condition;
Model Indirect:
olm IND Condition;

VARIABLE:
NAMES = Condition TP OR RR FR RECOG OLM;
Missing = all(999);
USEVAR = Condition rR olm;
MODEL:
olm ON rR Condition;
rR on Condition;
Condition;
Model Indirect:
olm IND Condition;
```