# THE EFFECTS OF COGNITIVE-MOTOR ENTRAINMENT ON LONG-TERM MEMORY ACROSS TWO PHYSICAL ACTIVITY MODALITIES

by

DAPHNE G. SCHMID

(Under the Direction of Phillip D. Tomporowski)

## ABSTRACT

Completing two tasks concurrently often leads to a decline in the performance quality of one or both tasks. However, an emerging body of literature suggests that cognitive-motor entrainment may alleviate dual-task cost and, in some cases, lead to a higher quality of psychological and physiological task performance than when the same tasks are performed in isolation. Through a theoretical review, primary experimental analyses, and secondary mediation analyses, the present dissertation seeks to understand how cognitive-motor entrainment may be used to enhance long-term memory retention through physical activity participation. In two crossover repeated-measures experiments, participants learned unique 40-word lists under three conditions: a cognitive-motor entrained, a traditional dual task, and a stationary control condition. In experiment 1, when participants learned words in a treadmill walking cognitive-motor entrained condition (words were presented on a screen every fourth stride), they retained more information during free-recall long-term memory assessments when compared to a stationary control ( main effect of time ($F(2,70)= 65.87$, $p < 0.001$, $\eta_p^2 = 0.65$) and condition ($F(2,70)= 3.63$, $p = 0.03$, $\eta_p^2 = 0.10$), no interaction ($F(4,140)= 1.73$, $p = 0.14$, $\eta_p^2= 0.05$)). In experiment 2, when words were studied under the cycle ergometer-entrained dual-task condition (word presentation was matched to cycling patterns), they were more easily free-recalled during delayed long-term memory testing than the word lists studied under the traditional dual-task or control condition (main effect of time ($F(2,70)= 94.07$, $p < 0.001$, $\eta_p^2 = 0.73$) and condition ($F(2,70)= 3.87$, $p = 0.03$, $\eta_p^2 = 0.10$)). In both experiments, no conditional differences were found in relation to recognition memory (accuracy or confidence) or motor coefficient of variation performance (gait parameters or cycling cadence). A secondary analysis of the data evaluated whether baseline long-term memory ability mediated cognitive-motor entrainment's mnemonic effects on long-term memory retention, but no effects of individual differences were identified. Altogether, these findings suggest that cognitive-motor entrainment may enhance long-term episodic memory retention regardless of the physical activity mode incorporated or foundational individual long-term memory differences. Further neuroimaging research is needed to clarify the underlying mechanistic effects of a cognitive-motor entrainment intervention and elucidate how the rhythmicity of stimuli presentation may confound the measured effects.

INDEX WORDS: entrainment, long-term memory, physical activity, cognitive-motor dual-task, acute physical activity intervention

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# CHAPTER 1

# INTRODUCTION

Is there an interface between the mind and the body? Philosophers and researchers across diverse fields have sought answers to this question via different theories of cognitive processes and physiological systems. The common goal underlying the mind-body question is to determine the cause of consciousness and the mechanisms underlying cognition. Some argue that every psychological construct and observable behavior can be traced to a physiological occurrence in the brain, while others say that the subjectivity and abstract character of cognition cannot be explained entirely through physical measurements. Nevertheless, many scientists' motivations for seeking an explanation to the mind-body question are analogous. By understanding plausible interactions between the body and the brain, there is potential to capitalize upon this information to maximize cortical processing and cognitive or motor functioning studies of how humans come to control their movements.

The concept of magnifying cognitive output through physical activity often arises when contemplating this interconnection. Cross-sectional research repeatedly reports a positive relationship between individuals with high fitness or physical activity levels and those with high levels of cognitive functioning (Hillman et al., 2008). Furthermore, research indicates that acute bouts of physical activity benefit cognitive functioning (Audiffren & André, 2019; Wilke et al., 2019), with the most prominent effects seen in executive functioning (Colcombe & Kramer,

2003) and, as a result, long-term memory and learning (Chang et al., 2012; Lambourne & Tomporowski, 2010; Roig et al., 2013).

In attempts to delineate results within a growing body of literature, recent meta-analyses further break down the relationship between movement and memory. Traditionally, the former is classified by dose and physical activity's temporal relation to cognitive encoding and consolidation. The latter is categorized by the specific type of memory used and the tests applied during long-term memory analyses. Discrepancies in experimental methodological design often lead to conflicting results, with some reviews reporting positive results (Jung et al., 2022; Roig et al., 2013; Wanner et al., 2020) and some reporting null effects (de Greeff et al., 2018). Qazi et al. (2024) address these issues by breaking down long-term memory outcomes according to the temporal relationship between physical activity and information encoding. Their results show that physical activity performed before or after encoding improved long-term episodic memory, while physical activity during encoding had no effects. However, an alternative body of cognitive-motor entrainment literature challenges these findings by suggesting that concurrent physical activity and cognitive processing may lead to increased performance in one or more tasks (Schmid, 2024).

The experiments outlined in the following chapters seek to clarify the cognitive-motor entrainment relationship and elucidate intervening variables that may influence the magnitude of the effect. Two experiments were conducted in which participants' long-term episodic memory retention was evaluated across three different dual-task encoding conditions. The experiments were exact replicas of one another apart from the physical activity modality implemented in the experimental design (walking on a treadmill or cycling on an ergometer). To contextualize the foreshadowed findings, the next chapter will provide an overview of the psychological constructs that underlie the physical activity-memory relationship and the theoretical foundations that seek to explain its underpinnings. Next, the concept of entrainment is introduced, and an interdisciplinary review of the current literature is provided. The document concludes by reporting the results from the two aforementioned experiments and discussing the implications of these findings.

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# CHAPTER 2

# LITERATURE REVIEW

## Psychological Constructs

### *Memory*

While many philosophers throughout history have pondered the notion of memory, the academic evaluation of memory began with the German psychologist Hermann Ebbinghaus (1885), who sought to validate the study of higher-order mental processes and provide quantitative values to seemingly abstract terms. Ebbinghaus introduced novel methods such as nonsense syllables and learning curves to help him quantify memory accumulation, retention, and the rate of forgetting. Though some of his methodological approaches are less popular today, his methods for psychological evaluation remain prominent (Slamecka, 1985). Ebbinghaus's early psychological experimentation provided a cornerstone for many modern models and theories used in memory research today.

Memory can be defined as the process by which the brain retrieves, stores, and recalls information. Each type of memory serves a unique function to support this complicated process. William James proposed the first division of memory into two storage processes: short-term, or "primary" memory, and long-term, or "secondary" memory (James, 1890). The former reflects conscious information processing, while the latter represents unconscious, stored information that will be retrieved in the future. Modern scientists most commonly delineate memory into three categories: (1) short-term, (2) working, and (3) long-term. Short-term memory refers to information (Cowan, 2008; Jonides et al., 2008) or motor responses (Adams & Dijkstra, 1966) that are held in a relatively accessible state, lasting for about three minutes. Individuals may not be aware of some information held in short-term memory. Closely related, working memory is a component system that an individual consciously uses to process and manipulate information in real-time (Baddeley, 2020). Working memory functionality allows an individual to use the information held in short-term memory (Cowan, 2008). Distinct from these two processes, long-term memory references a large store of knowledge where declarative and non-declarative information is held for future use.

To conceptualize memory, the Atkinson-Shiffrin information processing model uses a computer-based metaphor to explain the proposed mechanistic processes that support memory functionality (Malmberg et al., 2019). Memory is divided into three distinct steps: encoding, consolidation, and retrieval. During the *encoding* phase, attentional processes filter incoming sensory information and direct focus to the most important stimuli, as dictated by past experiences (Turk-Browne et al., 2013). Cognitive processes transduce these afferent sensory signals into conscious perception and create our individual understanding of the information held in working memory. Working memory stores information that is consciously being used. It supports executive processes, information manipulation in and out of long-term memory storage, and decision-making (Baddeley, 2010). Cortical capacity limits working memory to seven plus or minus two pieces of information (Saaty & Ozdemir, 2003). However, this can be overcome using memory strategies such as chunking or material rehearsal (Gruszka & Nęcka, 2017). The measurement of working memory is highly sensitive to factors such as dieting, medications, alcohol intake, and exercise (Blasiman & Was, 2018). Declines in working memory abilities are often associated with Alzheimer's disease (Kirova et al., 2015), Parkinson’s disease (Ramos &

Machado, 2021), and general amnesia (Quinette et al., 2006). Furthermore, individual differences in attentional control capabilities prevent distraction by maintaining appropriate levels of inhibitory function (Unsworth & Robison, 2020). Signaling from the prefrontal cortex (Lara & Wallis, 2015; Segal & Elkana, 2023) and activation of posterior sensory areas (Xu, 2020) and the posterior cingulate cortex (Hampson et al., 2006) and support these processes.

When information is no longer held in working memory, the information processing model poses that the brain uses a multifaceted process called *consolidation* to store information for future use (Chun & Turk-Browne, 2007). Immediately following the information presentation, recently activated synaptic activation patterns are theorized to be reinforced and ultimately reorganized with their repeated activation through long-term potentiation (Squire et al., 2015). This process relies heavily on hippocampal activation and neuromodulatory tagging during stimuli presentation (Schapiro et al., 2019). When stimuli are presented, chemical concentrations within the brain, such as dopamine and norepinephrine, are released, creating a neural association between the presentation of that information and the activation of particular neural communication networks.

The rate and timing of the degree of change in neuromodulator concentration is directly related to the efficacy of synaptic memory consolidation (Lehr et al., 2022). The synaptic tagging hypothesis argues that these neuromodulator chemical changes synaptically mediate consolidation processes (Redondo & Morris, 2011). By creating chemical “tags” associated with memories, the brain reinforces the saliency of facts or events, making them easier to recall later. The timing of consolidatory reinforcement is debated, with traditional systems consolidation theorists positing that this happens during sleep or rest the hours following encoding while contextual-binding theorists argue that contextually relevant information and memories are bound based on real-time environmental stimuli (Yonelinas et al., 2019). However, both perspectives agree that consolidation is necessary for effective memory storage and long-term information retention.

When information needs to be pulled from storage during recall, a memory trace is reconsolidated and held in working memory during the final *retrieval* stage. Memory retrieval success is limited by various factors, including the attentional demands of a task (Baddeley et al., 1984), individual differences in working memory capacity (Unsworth et al., 2012), and memory decay over time. Memory decay can be caused by neurogenesis-based forgetting, in which the structure of neural connections underlying memory storage shifts over time, interference-based forgetting caused by new stimuli presentation, or intrinsic forgetting associated with biochemical and molecular degradation over time (Hardt et al., 2013).

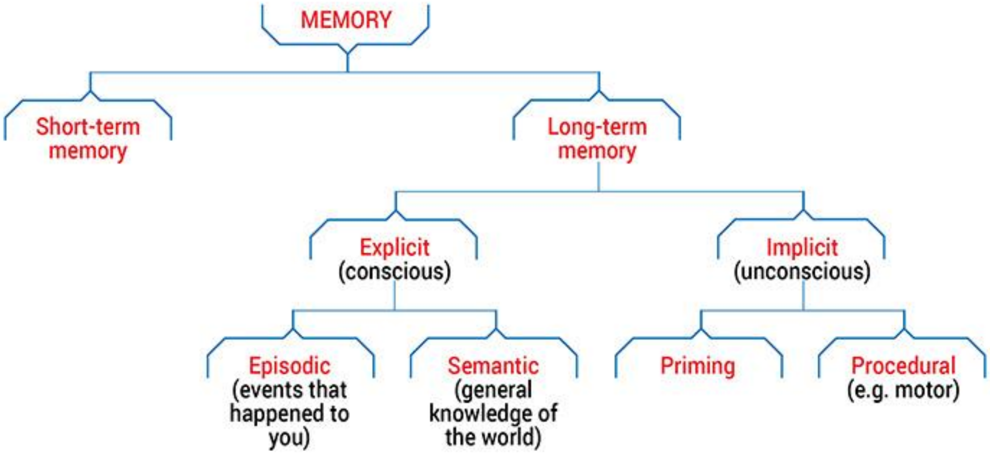


**Figure 2.1** Memory Classifications (Queensland Brain Institute, 2024)

Long-term memory is classified as declarative memory, which refers to explicit knowledge of facts and events, or non-declarative memory, which refers to implicit knowledge of motor skills, habits, etc. (Squire & Dede, 2015). Researchers suggest that these distinct memory classifications rely on different neural pathways supporting information encoding and retrieval (Squire, 1992; Squire, 2004). Declarative memory can be further delineated as either episodic memory, one's knowledge of life events, or semantic memory, knowledge of meaning, concepts, or understanding. Although intertwined with other forms of declarative memory, episodic memory is more commonly used in laboratory-based memory assessments because of its resistance to influence from one's prior knowledge of an event or topic (Renoult et al., 2019). Episodic long-term memory is the primary outcome measure used in the experimental procedures outlined in the following chapters. Long-term declarative memory tests include recall tests, in which responses are provided without a prompt, cued recall tests, in which responses are provided based on another piece of information, or recognition memory, in which a correct answer is selected from various options.

### *Attention*

The creation and retrieval of long-term memory relies on various underlying psychological processes. Wilhelm Wundt, the founder of psychology, was the first to suggest that involuntary and voluntary attention were integral to our ability to identify and contextualize information and to comprehend this information through apperception (Wundt & Judd, 1902). This notion aligns with the modern perspective that attention dictates working memory efficacy. Baddeley’s (2020) model of working memory argues that the central executive influences attentional processes to determine what type of information is accessible in working memory stores and what should be excluded.

Most scientists studying attention begin with the idea that the requirement of focus – whether controlled or automatic – leads to a specific situational perception. When choosing to evaluate it as a limited resource with a finite capacity, attention acts as a rate limiter of perception and working memory ability (Oberauer, 2019). Proponents of the Theory of Selection explain that the individual either makes a voluntary choice through "top-down" processing or an involuntary choice through "bottom-up processing" to direct attentional orientation (Schmidt et al., 2018). Both options require inhibiting attention to one thing in order to allow concurrently increased allocation of attention to another source. The Attentional Network Theory further explains the interplay of attentional functionality in which attention's alerting, orienting, and executive components are delineated (Petersen & Posner, 2012; Posner et al., 2006). The combined application of the aforementioned theories helps researchers conceptualize the aim of attentional orientation and understand how attention attenuates the interpretation of incoming sensory information.

A common point of debate amongst attention researchers revolves around the notion of the quantification or measurement of attention and its ultimate capacity. Most research throughout the first two-thirds of the 20th century applied single-channel or filter theories, which assume an individual has a fixed, undifferentiated attention capacity that can only focus on one factor at a time (Schmidt et al., 2018). This approach requires the assumption of parallel processing, where all information enters the brain through the same path and at the same rate. However, the constant input flow is theorized to be stunted when perceived information reaches a bottleneck (Broadbent, 1958; Lachter et al., 2004). Here, the limit of attentional capacity has been met, and an individual must make an inhibitory decision. The scientists who pioneered the Filter Theory of Attention, Broadbent and Deutsch, coined the term “filter effect” to describe this theorized phenomenon by which unnecessary information is excluded from conscious attentional allocation (Broadbent, 1958; Deutsch & Deutsch, 1963).

Early researchers exploring this theory assume that all processing requires some type of attentional allocation and that no stimuli can be processed automatically. Welford explained that this bottleneck would be met early on during stimulus identification as any secondary source of information would require an individual to choose one stimulus to which they would prioritize (Welford, 1967). Proponents of early-filter theories argue that the bottleneck is met just before response selection. Arguments for this approach allow parallel processing only when multiple sources of sensory information are being absorbed. However, once the bottleneck is reached, attentional allocation becomes all-or-nothing and has to be limited to one stimulus for a response to be selected appropriately. Late-filter theory pushes the bottleneck even further back in the stages of information processing by allowing for concurrent information processing until memory contact is made through stimuli associations (Keele & Neill, 1978; Schmidt et al., 2018).

While filter theories assume attentional allocation is constant across task types, alternative approaches decrease the rigidity of attentional limits. Flexible Allocation Theories propose that task requirements dictate attentional capacity by which attentional demand is proportional to task difficulty (Kahneman, 1973). This lens grants attention based on task complexity and permits parallel processing of incoming information. Flexible allocation theories permit the division of attention by rejecting the idea of a unitary capacity of attention that can only focus on one thing at a time. Because this model permits the division of attentional allocation, the trade-off of attention during concurrent processing is thought to lead to the prioritization of one stimulus, which causes a decrease in attentional capacities for another stimulus and limits the overall outcome. Alternatively, instead of viewing attention as a lake with one fixed volume, Multiple Resource Theories posit that attention should be viewed through the metaphor of multiple pools depending on concurrent task demands (Allport et al., 1972). Each pool is thought to supply a specific type of attentional processing. This means that while giving one stimulus attention, the amount of attention that could be granted to a different type of stimulus would not decrease.

Overall, the single-channel theory seems consistently supported by the literature on the decision-making paradigm (Schmidt et al., 2018). While parallel processing may occur early on, a response-selection stage requires individual attention to be allocated to determine an appropriate response. However, the specific location of that bottleneck seems to be unknown. When studying the phenomenon of dual-tasking or performing two different tasks concurrently, flexible allocation theory application permits the conceptualization of competition for neural resources. Discussion later in "The Physical Activity and Dual-tasking" section employs this perspective as it provides a functional foundation for interpreting dual-task cost.

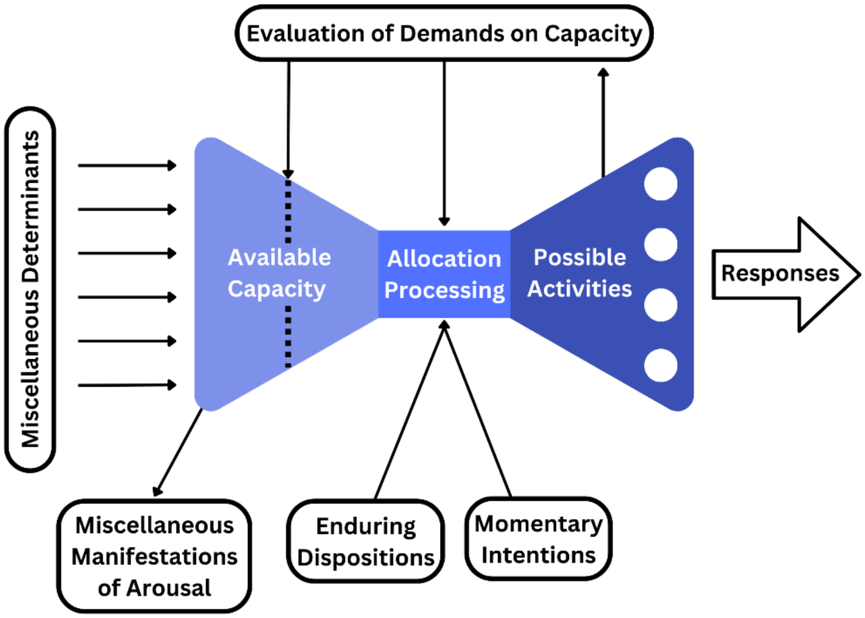


**Figure 2.2** A Stylized Version of Kahneman's (1973) Resource Allocation Model of Attention. Applying a flexible allocation model perspective, the resource allocation model describes how

concurrent stimuli processing forces an individual to optimize the distribution of their cognitive resources to produce effective responses. From the perspective of a dual-task scenario, this also reflects how limited cognitive resources may lead to decreased quality in task production.

## Physical Activity and Memory

Individuals often report changes in psychological functioning within the context of physical activity participation. Ultrarunners who engage in large bouts of aerobic activity commonly complain of brain fog, mental fatigue, and even hallucinations during races (Wollseiffen et al., 2016). In contrast, accounts of physical activity increasing memory, creative problem solving, and reasoning can be traced to antiquity, with Aristotle creating a school of peripatetic philosophers who walked as they debated topics. Modern reviews evaluating the relationship between physical activity and cognitive properties consistently report positive effects (Audiffren & André, 2019; Etnier & Chang, 2009; Gomez-Pinilla & Hillman, 2013; Landrigan et al., 2020; Loprinzi et al., 2018; Ludyga et al., 2020; Spirduso et al., 2008; Tomporowski, 2003; Wilke et al., 2019). However, inconsistent research methodology causes some researchers to question the strength of this effect (Ciria et al., 2023). This is likely because the cognitive benefits provided by physical activity vary depending on factors such as age, psychological diagnoses, the cognitive process being analyzed, etc. Individuals at either end of the lifespan tend to experience more cognitive benefits than young adults or adults (Álvarez-Bueno et al., 2017; Biazus-Sehn et al., 2020; Hillman et al., 2020; Meng et al., 2022). Cognitive benefits extend to individuals diagnosed with attention deficit hyperactivity disorder (Nejati & Derakhshan, 2021), depression (Dotson et al., 2021), and chronic brain disorders (Dauwan et al., 2021). Furthermore, physical activity has selective effects, with the most prominent effects seen in executive functioning (Colcombe & Kramer, 2003) and even more so in the higher-order cognitive processes of memory (Aghjayan et al., 2022; Lambourne & Tomporowski, 2010; Schmid et al., 2023; Wollseiffen et al., 2016).

The experiments discussed in the following chapters seek to further our understanding of the physical activity-memory relationship and are grounded in a recent theory-based systematic review of 42 experiments assessing the effects of acute bouts of physical activity on long-term episodic memory (LTM) (Qazi et al., 2022) and recent publications (Etnier et al., 2020; Loprinzi et al., 2021b). The review's methods categorized outcome measures by cognitive memory processes (e.g., free recall, cued recall, and recognition) rather than cognitive tests (e.g., paragraph recall, image recognition, recall of filmed scenarios) to reveal the process-specific effects of physical activity on LTM. Physical activity performed prior to memory encoding improved long-term episodic memory (d = 0.23). Still, it selectively affected free-recall (d = 0.40) tests of memory more than cued-recall (d = 0.08) or recognition (d = -0.06) memory. Physical activity following encoding improved memory (d = 0.33) but selectively affected recognition (d = 0.62) memory significantly more than free- (d = 0.19) or cued-recall (d = 0.14) memory. The pattern of effect sizes obtained indicates that acute physical activity exerts specific, rather than global, effects on episodic LTM and that this relationship needs further exploration.

## Foundational Theory and Neurobiological Mechanisms

Four primary theories, arousal theory, cognitive energetics theory, attention theory, and entrainment theory, postulate physical activity's effects on cognitive functioning and memory. (Schmidt-Kassow et al., 2023; Tomporowski & Qazi, 2020). Each theory focuses on one concept that researchers have deemed mediates the relationship between movement and cognition. While often tested in isolation, the theories are not mutually exclusive and are often intertwined when discussing experimental outcomes. They primarily rely on the neurological, physiological, and psychological rationale to propose explanations for the mechanisms underlying the physical activity-memory relationship.

*Arousal theory* proposes that physical activity-induced arousal will benefit cognitive processing due to changes in the signal-to-noise ratio of neurological systems. As a physiological theory, the primary notion is that acute physical activity temporarily changes neurobiological properties, priming them for cognition. This approach is founded on principles from the Yerkes-Dodson Law (Yerkes & Dodson, 1908), in which the strength of stimuli-induced stress or arousal is associated with performance outcomes. Supporters use an inverted U relationship to explain the expected relationship in which a moderate level of arousal during encoding would produce the largest cognitive benefit. However, meta-analytic results do not support this proposal, as they show cognitive benefits when dual-task exercise is performed before or after encoding but not concurrently (Qazi et al., 2024).

Instead of focusing on strictly physiological processes, *cognitive energetics theory* intertwines physiological and psychological concepts to take a more abstract approach. This argument originated from information processing models. When introduced, the theory was founded on three primary energetical mechanisms that controlled cognitive function, arousal, effort, and activation (Sanders, 1983). Limits of neural activity force attentional processes to allocate neural resources accordingly. Cognitive energetics theory has since been expanded and applied to the physical activity-cognition relationship and is often referred to as transient hypofrontality theory. The theory’s proponents explain that biological mechanisms qualify physical activity's influence on cognitive functioning using the following rationale,

> "Building on the fundamental principle that processing in the brain is competitive and the fact that the brain has finite metabolic resources, the transient hypofrontality hypothesis suggests that during exercise, the extensive neural activation required to run motor patterns, assimilate sensory inputs, and coordinate autonomic regulation results in a concomitant transient decrease of neural activity in brain structures, such as the prefrontal cortex, that are not pertinent to performing the exercise" (Dietrich, 2006).

Proponents of transient hypofrontality theory hypothesize that the intensity of physical activity limits physical activity's influence. Because of the high levels of neural activation required for high-intensity physical activity, the limited cognitive resources in the brain would be taxed at too great of a limit, minimizing the amount of cognitive activity that could be beneficial to cognitive functioning (Dietrich & Audiffren, 2011).

Following a similar rationale as cognitive energetics, *attention theory* also assumes that the brain has a fixed activity capacity. While some psychologists disagree on whether attention is a unitary or pooled construct, most would agree that its processes filter out irrelevant information to determine which stimuli should be consciously processed. Attention theory is particularly relevant when discussing the relationship between physical activity and memory. Attention and memory are bidirectional processes. Limited attentional allocation will circumscribe information encoding and, ultimately, long-term memory functioning. Because of attention's selective properties, Chun et al. (2007) propose that our prior experiences will inform attentional delineation and that the more a specific neural area is taxed, the more one's attentional bandwidth decreases. Required resources differ depending on the type of memory in function, with explicit episodic memory activation relying primarily on frontal and parietal lobe activation to direct attention and process incoming stimuli (Chun & Turk-Browne, 2007). Attention is particularly relevant in cognitive-motor dual-task scenarios, where multiple factors require attention simultaneously. Attention's limited capacity will dictate that cognitive resources must be split, likely resulting in a dual task cost and a decline in the quality of one or more output functions required to complete the dual task (Leone et al., 2017).

Attention is theorized to be influenced by temporal stimuli expectations. Neuroscientists propose that humans innately apply previous memories to incoming stimuli, maximizing attentional capacity and optimizing neural performance. Predictive timing synchronizes neural excitation (Arnal & Giraud, 2012), thus creating pockets of attentional enhancement (Jin et al., 2020) and augmenting memory (Thavabalasingam et al., 2016). Because of this, Turk-Brown et al. (2013) argue that researchers should conceptualize memory as a function of attention. Efficient neural functioning is thought to synchronously suppress and activate neural networks as directed by a singular motive. Extending this concept further, the theory of predicted encoding suggests that the brain anticipates what incoming information should look like and seeks to fill in the gaps with preexisting memories. Memory-based temporal expectations rely on lived experience to predict and facilitate neural activity. On the other hand, *entrainment theories* propose that oscillatory external stimuli will maximize sensory gain rhythmically. Research suggests that the mnemonic effects of memory-based and entrainment processes are shared, producing similar outcomes (Bouwer et al., 2020). However, EEG and ERP data suggest that the underlying mechanisms are distinct. Because entrainment theory provides the foundation for the primary hypotheses in the proposed experiments, it is discussed in more detail in the following chapter.

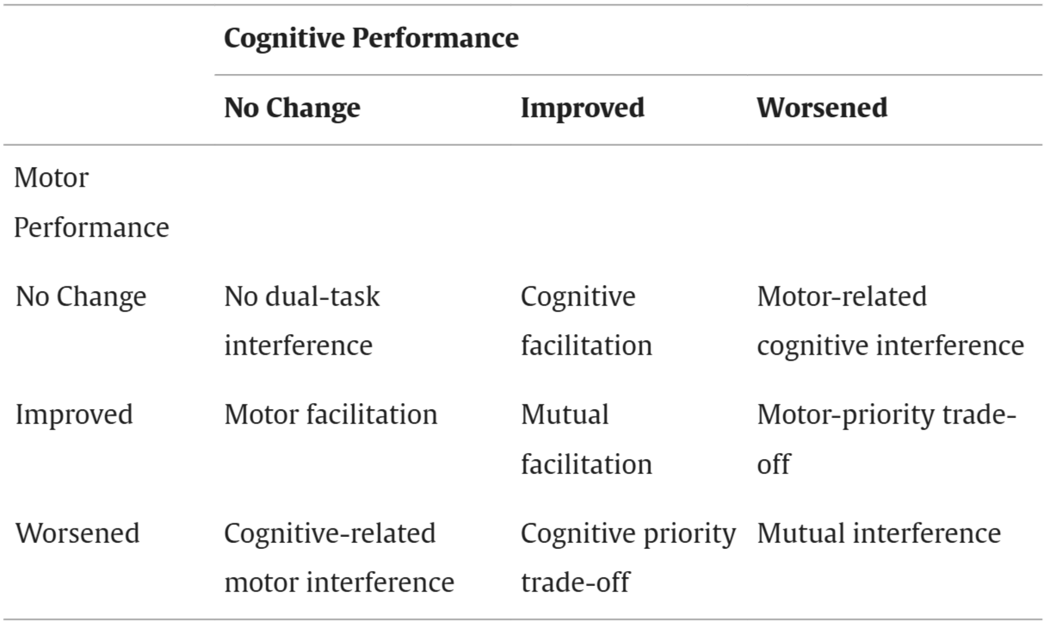
## Physical Activity and Dual Tasking

Dual-tasking or multitasking requires attentional process distribution and often leads to task prioritization, in which the completion of one task outweighs another. The term dual-task cost reflects a decline in performance due to competition for limited neural resources. Within the dual-task literature, tasks are most commonly defined as either a motor task, in which muscular output is required to perform the action, or a cognitive task, referencing brain functions. When motor dual tasking is evaluated, a probe technique is often used in which participants perform one primary, continuous motor task and respond to a probe stimulus that signals for a different motor action to be completed (Schmidt et al., 2018).

Seminal research using this paradigm revealed how different motor dual-task conditions led to varying amounts of motor interference (Welch, 1898). Another common dual motor task evaluation method focuses on gait and posture (Oh-Park et al., 2013). Participants walk (on a treadmill or overground) while performing another motor task simultaneously. Changes in either gait and posture or the quality of the secondary motor task's production provide insight into an individual's attentional prioritization and their distribution of mental efforts toward either motor task (Woollacott & Shumway-Cook, 2002). Commonly as a diagnostic and therapeutic tool, this technique helps researchers and practitioners identify motor deficiencies. Some examples in which a patient might be asked to perform a motor dual-task include when practitioners are trying to identify the magnitude of motor loss following a cerebrovascular accident or traumatic brain injury (Muci et al., 2022; Yang et al., 2007) or as a therapy to support mobility and activities of daily living in older adults (Brustio et al., 2018).

Similarly, research evaluating dual cognitive tasks measures the mental effort and neural resources needed to execute two tasks at one time successfully. In Koch et al.'s (2018).

integrative review of cognitive dual-task and task-switching research, the authors explain that the flexible trade-off notion of cognitive resources reflects the basic idea “that dual-task performance degrades to the degree the two tasks need to share a common capacity-limited resource.” Because the brain neural activation capacity is always limited, this concept extends further as well, and dual-task cost is also seen in the synchronous performance of a cognitive and a motor task (Schaefer, 2014). Even though these tasks produce distinct outcomes, the underlying neural structures involved are intertwined (Leone et al., 2017) and limited by the attentional and neurocognitive capacities of the brain (Bayot et al., 2018; Leone et al., 2017; Tomporowski & Qazi, 2020).



| | **Cognitive Performance** | | |
|---|---|---|---|
| | **No Change** | **Improved** | **Worsened** |
| Motor Performance | | | |
| No Change | No dual-task interference | Cognitive facilitation | Motor-related cognitive interference |
| Improved | Motor facilitation | Mutual facilitation | Motor-priority trade-off |
| Worsened | Cognitive-related motor interference | Cognitive priority trade-off | Mutual interference |

**Table 2.1** Plummer et al. (2013) Dual-task outcomes.

The nine options for cognitive-motor dual-task outcomes propose different ways in which task performance may be influenced during concurrent execution. Task success is influenced by many factors, including task complexity, attentional demand, cognitive effort, personal motivation, and task instructions.

However, integrating these different types of tasks does not always lead to a detriment in one or both tasks. Instead, when motor and cognitive tests occur concurrently, the relevant literature reveals a muddy and nuanced relationship that leads to varying psychological outcomes across experimentation.  Plummer et al. (2013) categorize nine outcomes that may result from a cognitive-motor dual-task cost. The outcomes differ based on the degree of positive or negative influence displayed in one or both tasks. Outcomes range from no interference or change in either task to mutual task performance benefits, mutual task performance detriments, and every combination in between. (See Table 2.1 for the full range of outcomes.) Multiple reviews on this topic identify variables underlying the inconsistencies in cognitive-motor dual-task literature, such as task complexity and resultant mental engagement demands (Tomporowski et al., 2015), the intensity of physical activity (Kimura et al., 2022), neurologic disorders (Fritz et al., 2015), and age (Brustio et al., 2017).

Recent studies have also examined the relationship between the timing of information presentation and cognitive and motor outcome variables during dual-task performance (Schmidt-Kassow et al., 2013d). When stimuli presentation during a cognitive-motor dual-task is entrained, neural patterns of excitation may be able to synchronize cognitive and motor signaling, decreasing the cortical effort needed for both tasks and potentially benefiting task production (Schmidt-Kassow & Kotz, 2008; Schmidt-Kassow et al., 2009).  The following chapter provides a systematic literature review of entrainment theory across multiple disciplines, contextualizing the research within the context of cognitive-motor dual-task experimentation (Schmid, 2024).

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# CHAPTER 3

# PROSPECTS OF COGNITIVE-MOTOR ENTRAINMENT: AN INTERDISCIPLINARY REVIEW

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# Abstract

Entrainment theory, a multidisciplinary concept referring to the automatic synchronization of oscillatory patterns, can be used to explain interactions across motor production, cognition, and environmental processing. This review summarizes findings from the three primary categories of naturally occurring neural entrainment: body-brain entrainment of involuntary self-produced rhythms, bottom-up entrainment between environmental stimuli and the brain, and top-down neural entrainment of self-produced processes. Studies evaluating entrainment's impact on cognition suggest that synchronized neural activation may alleviate cognitive constraints. Entrainment has also been therapeutically implemented to decrease motor production variation and enhance movement quality. When considering the evidence for entrainment's ability to decrease the attentional load of a task and increase cognitive or motor production quality, the oscillatory synchronization of a cognitive and motor task may be a promising technique that can be applied to dual-tasking. An emerging body of literature suggests that cognitive-motor entrainment may alleviate dual-task cost and, in some cases, lead to a higher quality of psychological and physiological task performance than when the same tasks are performed in isolation. We propose pathways for future research and emphasize the therapeutic relevance further experimentation on the topic of entrainment may provide. By understanding how to maximize neural entrainment's cognitive and motor benefits, scientists and practitioners may be able to harness its benefits to enhance learning and rehabilitative practices.

# Introduction

Entrainment theory, a multidisciplinary concept referencing the intrinsic propensity towards oscillatory pattern synchronization, appears as a common theme in work seeking to understand interactions among an individual's bodily movement, cognitive processes, and the surrounding environment. When applied to a psychological or a physiological context, entrainment refers to the alignment among or between different types of neural activity, including cortical intraneuronal communication and afferent or efferent activity between the body and the cortex. For example, an individual may consciously entrain a motor skill, such as foot tapping, with incoming sensory information, such as the beat of a song. Unconscious entrainment may also occur, where neural signals for incoming sensory information and cortical activity dictating an individual’s perception synchronize. Wherever multiple oscillatory patterns are presented, the potential for entrainment is present, no matter the source of the signal.

Psychologists apply principles of neural entrainment to conceptualize patterns of attentional control (Helfrich et al., 2019). Biologists explain the regulation of involuntary physiological processes of the autonomic nervous system with this principle (Lakatos et al., 2019). Linguists use neural entrainment to explain how we perceive and interpret the meaning of words, phrases, and sentences (Ding et al., 2017), and social cognitive neuroscientists posit that the alignment of inter-brain oscillatory communication underlies consciousness and perception (Valencia & Froese, 2020). However, while the assumed mechanism behind these lines of inquiry is the same, minimal interdisciplinary integration of the various contexts of entrainment has emerged. As a consequence, the translation of results and research progression has been limited. This review addresses this void by summarizing the most prominent lines of entrainment research to promote theory development and guide future directions in cognitive-motor entrainment experimentation. By broadening the scientific community's understanding of the implications of entrainment, researchers may be able to create tasks or environments that allow individuals to capitalize on the cognitive and motor benefits it provides.

## Neural Entrainment

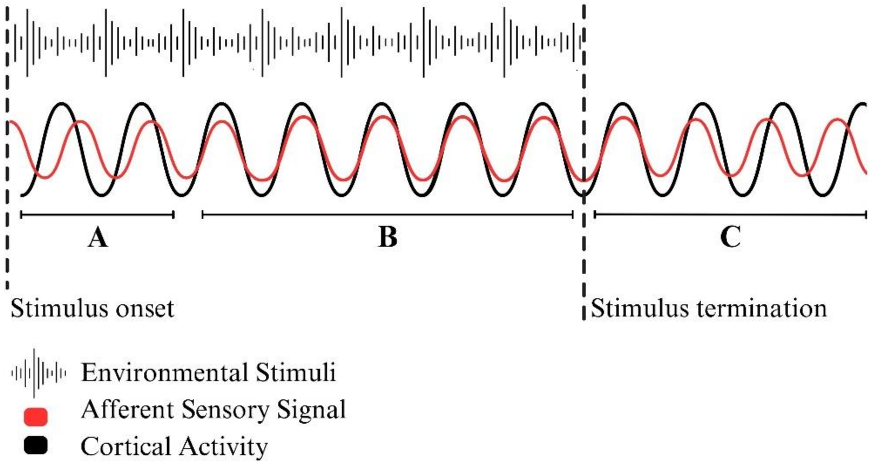


**Figure 3.1** A Stylized Example of Environmental Entrainment

A) Following a stimulus onset, afferent sensory signals will travel up the spinal cord towards the cortex. Depending on the timing and the intensity of the stimuli, incoming neural activity may cause a phase shift by which the frequency of cortical activity begins to align with sensory signals. B) When the two oscillating wavelengths align with one another, the system has reached bottom-up environmentally driven entrainment. C) When the external stimuli are terminated or change frequency, the two systems become unsynchronized, falling out of neural entrainment.

### *What is Neural Entrainment?*

The principle of entrainment originates from the field of physics and refers to the repetitive alignment of oscillatory patterns. Entrained processes create a stable, patterned relationship by which the peaks and troughs of independent wavelengths align (Figure 1). Notably, the repetitive, cyclical nature of oscillatory alignment distinguishes entrainment from single-phase synchronization (Bittman, 2021). When applied to neurophysiology, measurements of brain operations have led scientists to identify entrainment as a foundational element of cortical stimulation that enables the alignment of neural activity. In their comprehensive theoretical review, Lakatos et al. (2019) explain neuronal entrainment as a foundational mechanism underlying brain functioning communication that “set[s] an internal context for the modulation and interpretation of external signals or internal content based on the brain’s goals and expectations.” Although research has begun to evaluate the biological markers of entrainment, the rationale behind the proposed implications of neural entrainment primarily relies on models of neural activity and theoretical explanations (Beliaeva et al., 2021).

*The Theory of Dynamic Information Selection by Entrainment* (DISE) has been used to explain neural interactions among an individual's body, perception, and environment (Lakatos et al., 2019). Proponents of DISE argue that entrained oscillatory mechanisms create a rhythmic neural context that can align external stimuli patterns with internal information processing systems. As a supramodal mechanism enhancing the quality of neural functioning, entrainment modulates sensory processing by creating fluctuating patterns of high and low cognitive excitation (Calderone et al., 2014). When neural oscillations peak, attentional capacity is magnified to absorb pertinent information, and when they are at a trough, attention decreases to filter out unnecessary information.

While neural entrainment appears to be indiscriminate regarding the brain regions in which it occurs, research suggests that the frequency of entrainment likely dictates its functionality. For example, entrainment in the delta band is thought to have the largest impact on attentional processes (Lakatos et al., 2008). In contrast, β-frequency entrainment is more closely related to motor production signaling (Guerra et al., 2016). α-frequency neural entrainment is commonly associated with working memory, perception, and consciousness, while entrainment within the theta band is most commonly linked to memory formation and hippocampal activation patterns (Clouter et al., 2017; Hanslmayr et al., 2019). Furthermore, gamma-frequency entrainment is thought to influence attention and coordination of cognitive processing.

The entrainment of one neural frequency rarely occurs in isolation. When cross-frequency coupling occurs, low-frequency neural oscillations are thought to modulate high-frequency neural oscillations (Obleser & Kayser, 2019). Lakatos et al. (2008) demonstrate how gamma waves, which are also associated with attention and cortical processing, are influenced by delta band rhythmicity to produce synchronization across frequencies. Furthermore, cross-synchrony of neural frequencies contributes to working memory formation, perception, consciousness, and language comprehension (Obleser & Kayser, 2019; Palva & Palva, 2007). To explain frequency modulation and entrainment interactions, Fries (2005) proposed the communication-through coherence (CTC) hypothesis, which suggests that phase-locking of neural activation patterns may be the mechanistic foundation for neural communication. Rhythmic activation patterns at different frequencies are thought to contribute to the formation of selective pathways for cortical communication, promote cognitive flexibility, and prevent errors that may be caused by non-coherent activations or non-neural oscillations. Experimental evidence suggests that “gamma and beta rhythms modulate input gain, and their coherence subserves effective connectivity” (Fries, 2015). When principles from the CTC hypothesis and the DISE theory are conflated, the principle of entrainment can be applied to various settings to explain neural, behavioral, and motor functioning.

The neural substrates underlying entrainment are relatively unknown. EEG analyses evaluating the presence of entrainment throughout the brain suggest that phase-synchronization of neural activation patterns occurs indiscriminately across the cortex (Lakatos et al., 2019), but the mechanistic underpinnings of entrainment are less understood. Some researchers have begun to address this gap in the research by identifying relationships between neural entrainment and cognitive outcomes. For example, delta-frequency entrainment within the thalamocortical circuit has been linked to auditory processing (Barczak et al., 2018), and theta wave entrainment within the hippocampus and the medial temporal lobe is associated with memory encoding and retrieval (Hanslmayr et al., 2019; Köster et al., 2019). However, further research is needed to clarify these relationships to reveal the underlying mechanisms and neuronal substrates behind neural entrainment.

### *Neural Entrainment and Psychological Theory*

When addressing the behavioral impact of entrainment, DISE predicts that stimuli synchronization enhances cognitive functioning through temporally concurrent processes that facilitate one's attention to and perception of stimuli (Haegens & Zion Golumbic, 2018). Whereas neurophysiological measurements provide helpful insight into the neurobiological activation patterns underlying cortical activity, psychological theories and models help scientists conceptualize the behavioral outcomes associated with biological changes through abstract descriptions of cognitive functioning (Kay, 2018). The following section briefly discusses entrainment theory in relation to prominent psychological theories of attention and information processing.

Attention is assumed to be limited and selective. When interpreting attention through the *Theory of Selection*, an individual is thought to direct their attentional orientation through voluntary choices using "top-down" processing or involuntary choices using "bottom-up processing" (Schmidt et al., 2018). Both options require the concurrent inhibition of attention to an alternative factor to increase the allocation of attention to one stimulus. After information passes through the attentional filter, it must be organized and acted upon. Because attention constrains stimuli processing, one's perception will change when a situation requires attentional reallocation. To explain this procedure, *Information Processing Theory* uses a computational metaphor that compares the human brain's ability to take in, process, and respond to information to a computer system. The three main stages contributing to information processing are stimulus-identification, response-selection, and response-execution. Stimulus identification relies on the sensory system to detect environmental stimuli and send afferent signals. The response-selection phase requires the individual to determine how to respond to a detected stimulus, and the reaction is translated into a neural command in the response-programming stage.

Because neural activity is viewed as a limited capacity resource, the foundational concepts of attention and information processing have been integrated into broader theories that explain how cortical processes may interact and influence cognitive output as a whole. *Cognitive Energetics Theory* proposes that all cortical activity is limited by regulatory costs of neural activation that force attentional processes to divide and allocate the arousal, effort, and activation of resources required to perform a task (Sanders, 1983). *Cognitive Load Theory* extends this notion by explaining how a fixed processing capacity also bounds the resultant information that passes through attentional filters. Therefore, this cortical activity capacity rate limits the brain's ability to identify a stimulus and respond through the information processing pathway. But what if there was a way to expand functioning capacity?

When considering neural entrainment's implications within the context of the theories above, aligning neural oscillations would likely minimize noise across cortical signals and create patterns of expected activation, decreasing neural load. In fact, multiple cognitive processing theories propose psychological principles that complement the neurobiological implications of entrainment theory. *The Dynamic Attending Theory* (Bauer et al., 2015; Jones, 1976; Phillips-Silver et al., 2010), which states that sequences presented in a predictable pattern facilitate stimuli processing, and the *Neural Resonance Theory* (Large & Snyder, 2009), which explains how the brain synchronizes processing of non-periodic stimuli, are often used to explain neural entrainment's effects. These theories suggest that rhythmic, anticipated events will be more efficiently encoded due to enhanced perceptual sensitivity (Hanslmayr et al., 2019). Within the context of neural entrainment, both theories would support the notion that by aligning neural activation patterns, the cognitive effort required to carry out the entrained functions decreases, freeing up more cortical space, magnifying the quality of cortical output (See Figure 2 for more information.)

While there are research findings supporting the causal propositions posed by these theories, their mechanistic foundations await determination. In their critical review of entrainment's impact on sensory processing, Haegens et al. (2018) cautioned readers of methodological flaws in entrainment studies and emphasized the need to assess the relationship between neural entrainment and perception. By breaking down entrainment's driving factors, the following sections will summarize the current understanding of its biological and neurological foundations and propose ways to integrate concepts and methodological principles from different research fields exploring the concepts of neural entrainment.

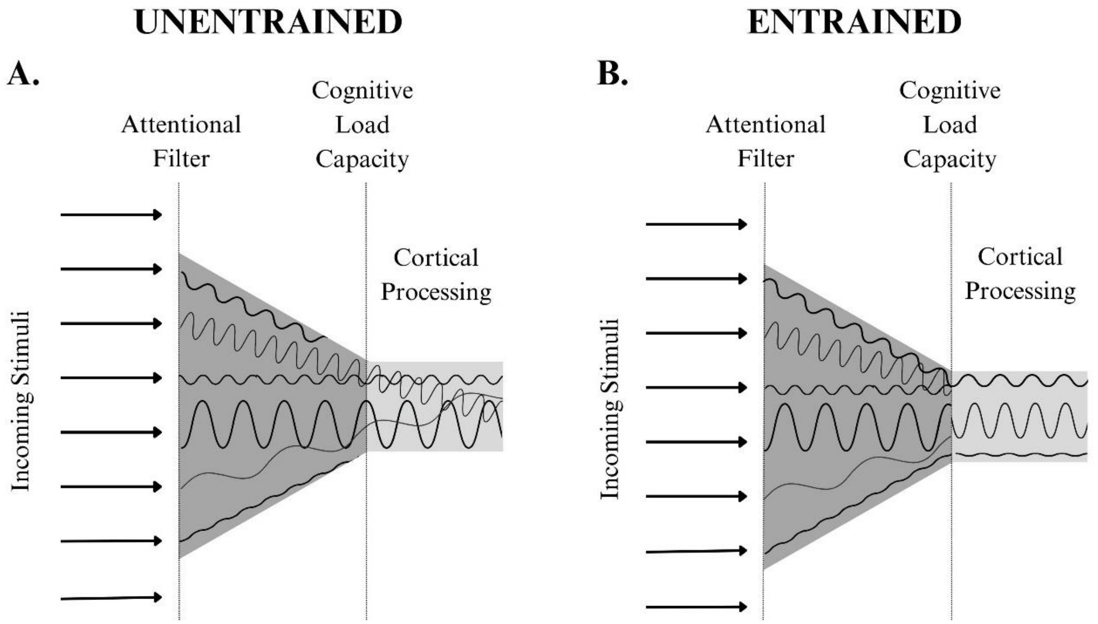


**Figure 3.2** A Theoretical Representation of Neural Entrainment's Effects on Cognitive Processing

The arrows on the left of each diagram represent different sources of stimuli. According to the Theory of Selection, an individual's goals and past experiences will dictate what information passes through the attentional filter. This information is then organized and transmitted to the appropriate areas in the cortex. The unique qualities of each stimulus create a neural wavelength with a distinct frequency and amplitude shown at the center of each diagram. In diagram A, the conflicting neural signals create noise, increasing cognitive load. In this instance, a cortical processing capacity, detailed in Cognitive Load Theory, would prevent the transmission of all of the stimuli being attended to and limit cognitive functioning. However, in diagram B, the entrainment of multiple sources of stimuli increases one’s attentional capacity as the noise across the entrained wavelengths is minimized. This enhances the volume of information one can attend to, transmit to the cortex, and process through cognitive functions. Ultimately, neural entrainment allows an individual to maximize cognitive processing, enhancing their ability to perceive and respond to information from their body and environment.

## Categories of Neural Entrainment

Neurophysiological evidence points towards three primary categories that cause neural entrainment: body-brain entrainment of involuntary or voluntary self-produced rhythms and neural activity, artificially induced neural entrainment from noninvasive stimulation, and entrainment between environmental stimuli and the brain (Lakatos et al., 2019). The former are top-down processes in which neural activation patterns and cognitive perceptions drive entrainment effects, while the latter category is a bottom-up process in which external, environmental factors influence cognitive and motor output. Because of similarities across the behavioral and cognitive factors involved in different forms of entrainment, Figure 3 organizes each type along a continuum based on whether their driving factors rely on top-down or bottom-up processes. For readers who would like an in-depth explanation of entrainment differentiation, Lakatos et al. (2019) provide a helpful review of the mechanisms behind and roles of neuronal entrainment.

### *Self-Produced Entrainment*

Self-produced entrainment uses naturally occurring physiological activation patterns to align cortical oscillations. The innate process relies on endogenous activity to initiate entrainment. One's intention or lack thereof to instigate self-produced entrainment dictates the process's classification as voluntary or involuntary.

*Voluntary:* With the ability to supersede other forms of naturally occurring entrainment, voluntary self-produced entrainment describes a top-down process by which the conscious initiation of a motor process influences the rate of sensory sampling and perceptual processing. Studies using EEG analysis show how efferent neuromotor signal oscillations entrain with afferent sensory signals. This process typically occurs through rhythmic environmental sampling, which is thought to enhance intracortical communication and decrease neural demand by creating patterns of attentional focus that benefit perceptual ability. For instance, producing visual saccades or sniffing patterns allows the brain to anticipate sensory input and allocate attention to incoming stimuli in a synchronized pattern (Schroeder et al., 2010). Other examples include how fine and gross patterned limb movement contributes to the perception of auditory stimuli (Falk & Dalla Bella, 2016) or how distinct rhythmic speech patterns influence one's understanding of language and verbal communication with others (Zoefel, 2018). Ultimately, self-produced voluntary entrainment allows individuals to optimize goal-directed neural activity through conscious prioritization, allowing it to supersede all other involuntary, naturally occurring entrainment patterns discussed below.

*Involuntary:* Involuntary self-produced entrainment primarily occurs through interactions between cortical activity and autonomic nervous system activation patterns that drive biological rhythms, including heart rate regulation, respiration patterns, and the glycolytic cycle (Jiménez et al., 2022). Some researchers propose that this type of entrainment likely provides an evolutionary advantage by decreasing noise across interoceptive processing, magnifying the brain's available resources for cortical activity (Buzsáki et al., 2013). As the body and the brain constantly work to maintain vital physiological processes, neural activation patterns are thought to align and interact to maintain homeostasis and benefit cognitive functioning (Boyadzhieva & Kayhan, 2021). To explore this concept, a study by Garfinkel et al. (2013) visually presented word lists in alignment with real-time electrocardiograph (ECG) heart rate readings, producing an induced state of involuntary entrainment. The authors report that memory for words was better when stimuli were presented in line with diastole and worse when presented during systole. These findings suggest autonomic signal entrainment with cortical oscillations may influence cognitive functioning due to entrainment's modulation of attentional processes (Garfinkel et al., 2013). Nevertheless, more research is needed to clarify this relationship, as little is understood about the mechanisms that drive entrainment within the body and between the body and the brain.

In summary, self-produced forms of entrainment are driven by internal signaling, whether consciously produced through voluntary entrainment or driven by subconscious innate processes as involuntary entrainment. Voluntary entrainment relies on top-down signaling initiated by prefrontal cortex activity. In contrast, involuntary entrainment lies in the middle of the continuum between top-down and bottom-up processing. Please see Figure 3 for further delineations regarding entrainment categories across the top-down – bottom-up entrainment continuum.

### *Artificially Induced Entrainment*

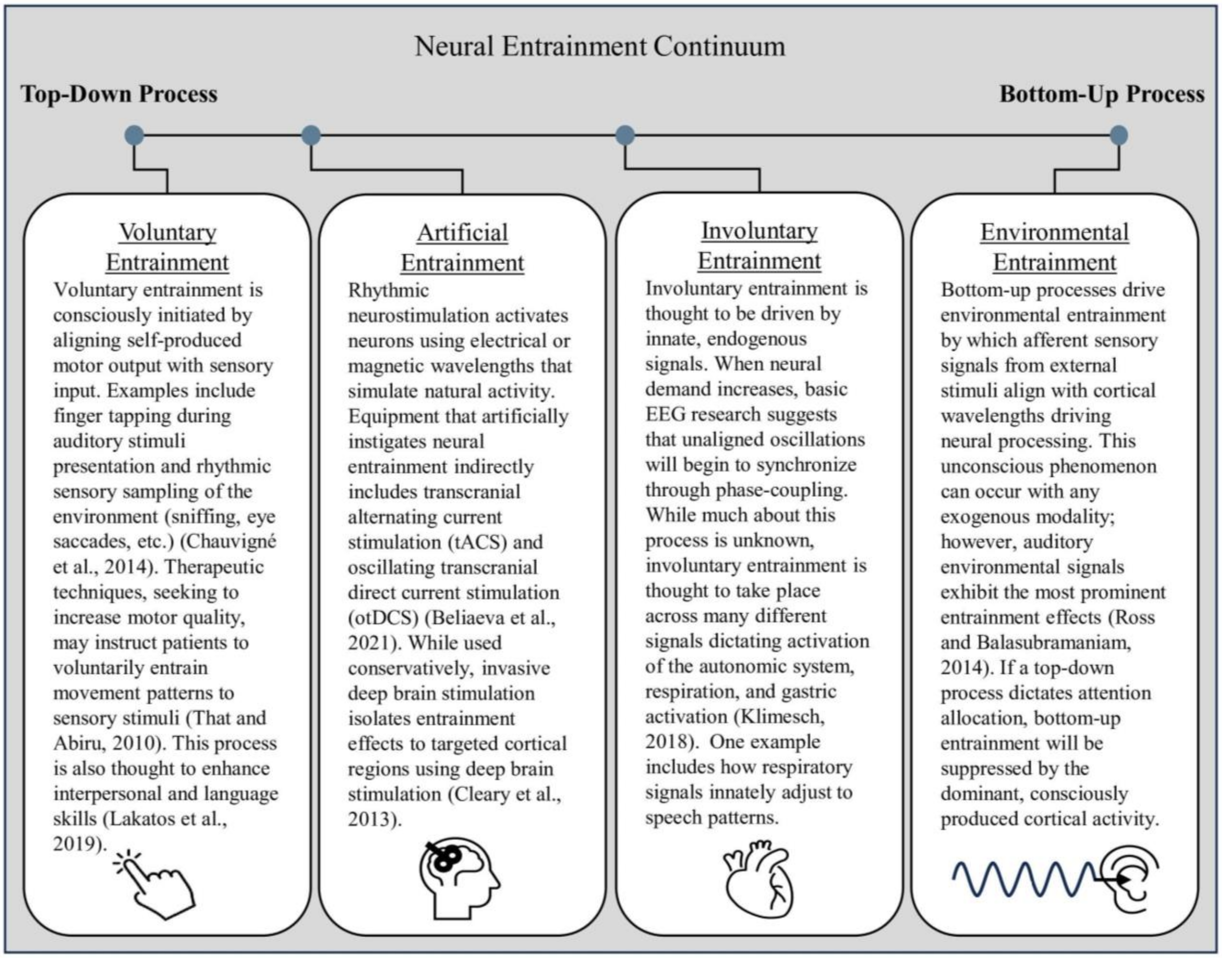
Top-down neural entrainment can also be induced using neuromodulatory techniques. Invasive and noninvasive neural therapies influence cortical activation patterns through the artificial delivery of electromagnetic stimuli that trigger neural activity. Transcranial magnetic stimulation (TMS) and transcranial alternating current stimulation (tACS) are most frequently used to produce entrainment synthetically by synchronizing natural neural activity with an oscillating input stream of magnetic or electrical currents. These noninvasive entrainment techniques have enhanced perceptual ability, working memory, and motor production quality (Helfrich et al., 2014; Thut et al., 2011). Neural entrainment may also be artificially induced using deep-brain stimulation to more accurately target specific cortex regions. Using this invasive technique, deep brain stimulation has been shown to entrain neural activity at the globus pallidus, disrupting atypical neural activity caused by Parkinson’s disease (Cleary et al., 2013) and at the medial septum as a treatment for temporal lobe epilepsy (Cole et al., 2022). However, some studies evaluating the effects of invasive deep-brain stimulation on entrainment and cognition report contradictory effects. When cortical areas associated with memory are stimulated at a frequency that leads to neural entrainment, negative (Kim et al., 2018) and positive (Inman et al., 2018) cognitive effects have been reported.

Both invasive and noninvasive artificially induced neural entrainment are promising techniques that may alleviate some neurological conditions and influence cognition. It is important to note that most studies evaluating the effects of artificially produced entrainment use a small sample size. Replication studies using larger sample sizes are needed to help clarify how different neural stimulation techniques may vary in their ability to induce entrainment and influence cognitive functioning successfully (Hanslmayr et al., 2019).

### *Environmentally Produced Entrainment*

When entrainment is environmentally produced, afferent neural activity from sensory stimuli aligns with intracortical wavelengths. Research findings suggest that this bottom-up classification of neural entrainment is a natural, involuntary process. To achieve environmental entrainment, the incoming oscillatory stimulus produces systematic patterns of neural information that align with pre-existing neural activity. The stimuli must originate from an external source and cannot be generated through individual motor production, such as auditory information from self-generated speech or tactile information from finger tapping. Because of the brain's limited capacity for resources, specifically attention, the incoming stimuli that present the strongest will supersede any other incoming oscillatory information and be the strongest candidate to produce environmentally-driven entrainment (Calderone et al., 2014). While bottom-up entrainment is automatic, it can be superseded by top-down, voluntary entrained signals. This permits individuals to suppress incoming stimuli and produce a desired outcome (Lakatos et al., 2019).

Numerous studies report how neural entrainment of repetitive and predictable sensory stimulation is related to enhanced cognitive functioning (Gu et al., 2015; Hanslmayr et al., 2019; Lakatos et al., 2019; Schmidt-Kassow et al., 2013c; Schmidt-Kassow & Kotz, 2008; Schmidt-Kassow et al., 2009). Researchers commonly alter the timing of stimuli presentation to systematically evaluate the effects of environmental entrainment. Results tend to be relatively stable, with the predictable, entrained presentation of stimuli facilitating memory (Brochard et al., 2013) and attentional processes (Bolger et al., 2013). Entrainment of neural oscillations during cognitive tasks can be found in all electroencephalography (EEG) bands, with common targets at P300 event-related potentials (ERPs)(Schmidt-Kassow et al., 2009), P600 ERPs (Canette et al., 2020; Schmidt-Kassow & Kotz, 2008), and FN400 ERPs (Garcia-Argibay et al., 2019), which are associated with selective attention and stimuli processing, language processing. Furthermore, bottom-up sensory entrainment studies report positive impacts on memory processes in particular (Benchenane et al., 2011). For example, experiments presenting visual stimuli rhythmically (Jones & Ward, 2019) or paired with a cyclic light flicker paradigm (Williams, 2001) report enhanced memory processing and the presence of neural entrainment through EEG analyses. The rhythmicity and predictability of stimuli presentation are thought to influence neural processing and provide mnemonic effects by creating windows of enhanced attention that facilitate item encoding.



Voluntary Entrainment

Voluntary entrainment is consciously initiated by aligning self-produced motor output with sensory input. Examples include finger tapping during auditory stimuli presentation and rhythmic sensory sampling of the environment (sniffing, eye saccades, etc.) (Chauvigné et al., 2014). Therapeutic techniques, seeking to increase motor quality, may instruct patients to voluntarily entrain movement patterns to sensory stimuli (That and Abiru, 2010). This process is also thought to enhance interpersonal and language skills (Lakatos et al., 2019).

Artificial Entrainment

Rhythmic neurostimulation activates neurons using electrical or magnetic wavelengths that simulate natural activity. Equipment that artificially instigates neural entrainment indirectly includes transcranial alternating current stimulation (tACS) and oscillating transcranial direct current stimulation (otDCS) (Beliaeva et al., 2021). While used conservatively, invasive deep brain stimulation isolates entrainment effects to targeted cortical regions using deep brain stimulation (Cleary et al., 2013).

Involuntary Entrainment

Involuntary entrainment is thought to be driven by innate, endogenous signals. When neural demand increases, basic EEG research suggests that unaligned oscillations will begin to synchronize through phase-coupling. While much about this process is unknown, involuntary entrainment is thought to take place across many different signals dictating activation of the autonomic system, respiration, and gastric activation (Klimesch, 2018). One example includes how respiratory signals innately adjust to speech patterns.

Environmental Entrainment

Bottom-up processes drive environmental entrainment by which afferent sensory signals from external stimuli align with cortical wavelengths driving neural processing. This unconscious phenomenon can occur with any exogenous modality; however, auditory environmental signals exhibit the most prominent entrainment effects (Ross and Balasubramaniam, 2014). If a top-down process dictates attention allocation, bottom-up entrainment will be suppressed by the dominant, consciously produced cortical activity.

**Figure 3.3** The Neural Entrainment Continuum

Top-down entrainment processes influence cortical activation patterns that alter attentional orientation and efferent signaling. In contrast, bottom-up entrainment, represented on the far right of the continuum, is driven by afferent neural signaling that travels up to the cortex, influencing cortical activation patterns.

In summary, each category of neural entrainment results in the alignment of oscillating wavelengths. Though the resultant entrainment may be the same, self-produced, artificially induced, or environmentally produced entrainment categories are distinguished by the phase shift's driving factor. For example, an individual may produce voluntary entrainment by matching their steps to the beat of a song. However, the same result could unconsciously be produced through the influence of environmental entrainment. (Please see Repp and Su (2013) for a helpful review of sensorimotor primary studies on this topic.) EEG findings suggest that entrainment's cognitive benefits regarding the frequency and location of cortical activation are indiscriminate, making it a versatile technique that can be used to enhance desired cortical activity and suppress atypical neural functioning. Research across disciplines points towards the importance of oscillatory activity for physiological functioning and the benefits of neural entrainment in various applications. While promising, there are inconsistencies across this body of research (Haegens & Zion Golumbic, 2018). More research is needed to clarify the mechanisms behind entrainment and to understand the intricacies of its cognitive effects.

## Clinical Applications of Neural Entrainment

Neural entrainment is thought to maximize cognitive processing potential and decrease cortical activity strain (Calderone et al., 2014). In the 1990s, rehabilitative programs designed to enhance the quality of movement production began to popularize, applying entrainment principles to therapeutic techniques. Because entrainment of neural activity is thought to increase the efficiency and efficacy of neural communication, researchers have suggested that oscillatory rhythms may synchronize with repetitive neural activity, producing stable motor activation patterns (Chauvigné et al., 2014). Auditory and visual stimuli are most frequently used to instigate environmentally-driven entrainment in rehabilitative practices. Because the influence of these stimuli is driven by bottom-up processes, this allows the researcher or therapist to make slight adjustments to the stimuli presentation, maximizing the potential for beneficial effects.

### *Entrainment Therapy*

Research evaluating rhythmic auditory stimuli is particularly popular in neuromotor rehabilitation techniques that draw from principles found in neurological music therapy (Thaut, 2013). Neurobiological foundations lie in auditory projections within the cerebellum and audio-motor pathways in the cortex and reticulospinal tract of the spinal column (Thaut & Abiru, 2010). The proximity of cortical auditory-motor pathways facilitates the synchronization of neural activation patterns across these brain regions and increases the likelihood of neural entrainment between oscillations from afferent auditory signals and efferent motor signals. Entrainment is driven by the period, or the interval between two beats, of rhythmic auditory signals (Thaut et al., 2014). While many individuals will unconsciously undergo bottom-up entrainment by which their motor signals align with auditory oscillations, many people require cuing to instigate top-down entrainment by which the individual seeks to match their motor activation periods to the oscillations of auditory periods from external stimuli (Dotov et al., 2019; Moens et al., 2014). Because a rhythmic sound requires consistent periodization, this type of auditory-motor entrainment is thought to stabilize efferent motor signals that produce a cyclical movement pattern. A variety of motor production patterns have been shown to be influenced by auditory cuing, including walking and running gait, and hand functioning. (Buhmann et al., 2018; Thaut & Abiru, 2010; Thaut et al., 2014).

Understanding the relationship between neural activation, auditory stimulation, and motor production facilitates the use of rhythmic auditory stimulation as a rehabilitative tool. This approach seeks to synchronize motor movements with rhythmic stimuli to decrease motor production variation and alleviate neuromotor impairments. A common way to test this approach is to use a paradigm in which participants tap their fingers to an auditory rhythm. When applied, individuals tend to be able to cue motor functions more efficiently, as reflected through changes in neural activation patterns measured with EEG and electromyography (Thaut & Abiru, 2010). Similar results are also frequently seen during auditory-motor coupling of gait patterns in a healthy, young adult population through measurements of relative stepping phase angle, resultant stepping vector length, stepping asynchrony, and tempo matching accuracy (Moumdjian et al., 2018).

Additional research has shown that the mechanistic benefits of cognitive-motor entrainment translate to real-world settings to enhance and optimize walking and running performance in individuals with different pathologies (Buhmann et al., 2018). Examples of the successful implementation of rhythmic auditory stimulation include reports of increased gait quality in children with cerebral palsy, older adults following a cerebrovascular accident, and adults with Parkinson's disease (Ghai et al., 2018; McIntosh et al., 1997; Thaut & Abiru, 2010). While benefits from auditory-motor entrainment therapy are consistently found, individual differences may impact the magnitude of its effect. Factors that may influence this relationship include gender (Buhmann et al., 2018), unique neurophysiological diagnoses (Schaefer, 2014a), age, and stage of sensorimotor development (Thaut & Abiru, 2010). Ongoing research seeks to further clarify which individuals may have the highest propensity to benefit from auditory-motor entrainment therapy and understand its most appropriate applications. Along with the clinical strategies discussed above, which rely on self-produced voluntary entrainment and bottom-up, environmental entrainment, artificially induced entrainment also shows promise in therapeutic application.

### *Artificial Entrainment and Motor Production*

Artificially induced entrainment techniques typically activate the cortex through electrical or magnetic stimulation. Research suggests that neural entrainment is instigated when artificial electrical signals stabilize atypical patterns of neuronal firing (Cleary et al., 2013; Sermon et al., 2023). The stable pattern of neural activity within a specific brain region encourages other sources of neural activity to entrain to the emitted wavelength's frequency and amplitude. As many movement disorders are instigated by atypical neural activation of alpha motor neurons, neural entrainment therapies seek to decrease the coefficient of variation across motor signal activation. In individuals with Parkinson's disease, deep-brain stimulation may be used to enhance neuromodulation. This therapy has effectively diminished pathological tremors when applied at the subthalamic nucleus and the globus pallidus internus (Fischer et al., 2020; Rodriguez-Oroz et al., 2005). Furthermore, tACS entrainment has been shown to help individuals manage motor control output by stabilizing neural oscillation patterns disrupted by neurodegenerative diseases or cerebrovascular or cardiopulmonary events (Takeuchi & Izumi, 2021). Experimental applications of tACS-induced entrainment also report enhancements in motor functioning following stroke (Hsu et al., 2012) and alleviate cognitive deficits associated with dementia (Elyamany et al., 2021).

Using noninvasive brain stimulation to induce entrainment artificially may also accelerate the development of motor learning and skill development. Researchers have begun to explore how augmented neural stimulation may influence the physiological and cognitive aspects of motor production. By applying sinusoidal electrical stimulation in targeted brain areas, tACS is thought to produce entrained patterns of neural activation that magnify the rate of motor learning (Colzato et al., 2017). Following the rationale used to describe entrainment’s effect on psychological outcomes, the synchronization of neural activity creates fluctuating patterns of attentional capacity, facilitating learning. Experimental findings report that tACS may decrease interference effects and stabilize a motor learning task (Pollok et al., 2015). It is important to note that while studies report tACS’s facilitation of motor learning, there is little evidence to show that entrainment is the true mechanism of action behind these results. Additionally, positive outcomes have been reported in studies completed in controlled environments with small sample sizes. As of now, there is little evidence to support that these findings will translate to alternative environments or lead to alterations in sports or physical activity performance in a competitive environment.

Artificially induced entrainment introduces a unique perspective when compared to alternative forms of entrainment. Although procedural restrictions limit its application in many real-world settings, experimentation using this form of entrainment provides insight into the techniques by which entrainment’s effects and therapeutic potential may be maximized. Because artificial entrainment allows researchers to target distinct regions in the brain, this methodology can be used to parse out whether or not specific brain regions may differ in their ability to benefit from neural entrainment. Further exploration on this topic may allow clinicians to determine which pathologies benefit most from entrainment therapy and learn which application techniques hold the most promise of positive effects.

## Dual-Task Cognitive-Motor Entrainment

As phase synchronization of neurobiological activation patterns may benefit both motor and cognitive functions separately, entrainment research emerged to explore the effects on cognitive-motor dual-task performance. The main questions being: Would cognitive-motor entrainment influence the quality of cognition, motor production, or both? and Would these effects result in positive or negative changes? Because dual tasks require concurrent allocation of attentional processes, they are often associated with a decline in the production quality of one or both tasks. However, when considering the evidence for entrainment's ability to decrease the attentional load of a task and increase cognitive or motor production quality, the oscillatory synchronization of a cognitive and motor task may alleviate the traditional costs of dual-task performance.

Traditionally, when cognitive and motor tasks are performed in tandem, adults often experience null or adverse effects on cognitive output (Loprinzi et al., 2019a; Loprinzi et al., 2019b) and a possible decline in the quality of motor production as well (Plummer, 2009). Because of the brain’s finite attention and cortical processing capacities, simultaneously performing two tasks requires prioritizing and selecting tasks to direct attention toward. However, when the secondary task is not allocated the same cognitive resources as it would have received in a single-task scenario, this often leads to a decline in the secondary task’s performance quality. In their review of the neural correlates associated with cognitive-motor dual-tasking, Leone et al. (2017) report that dual-task conditions often instigate cortical activity in areas of the brain that were not associated with activity during either single-task performance. The increased cognitive load resulting from dual-task interference is often observed across cortical areas associated with information processing and motor control. These findings suggest that the decline in behavioral performance often seen as a result of cognitive-motor dual-tasking is likely due to increased cortical load and strained cognitive resources.

The neurobiological evidence, which indicates that increased cortical effort is required to perform a cognitive-motor dual-task, supports conclusions presented previously concerning theoretical explanations of cortical processing (i.e., The Theory of Selection and Cognitive Load Theory). Furthermore, the predictions derived from these theories suggest that neural entrainment may potentially alleviate a portion of dual-task cost. While a task's intensity or difficulty may influence the magnitude of change instigated by entrainment's effects, neural entrainment's ability to decrease a task's cognitive load provides a helpful strategy by which individuals may be able to overcome dual-task interference. A recent review of cognitive-motor interference noted that experiments implementing entrainment methodologies tend to contradict the norm of reporting dual-task performance detriments and instead have found mnemonic or beneficial cognitive effects (Tomporowski & Qazi, 2020). Through systematic experimentation evaluating the influence of cognitive-motor entrainment on task performance, these studies indicate promising behavioral and neurological effects. For example, Schmidt-Kassow et al. (2010) asked young adults who were low-span readers to encode French-German word pairs in tri-weekly training sessions across three weeks. During the training sessions, participants cycled to a rhythmic, auditory beat or sat stationary on an ergometer as auditory stimuli were presented consistently. At the end of each week, participants completed a cued recall test. For individuals in the cycling condition, word presentation was entrained to the participant's rate of cycling.

While groups acquired the words at a similar rate across weeks, the spinning groups always produced higher free recall memory scores at every testing session. ERP results from separate EEG analyses of a very similar task show that participants in the spinning group had larger N400 peaks that were synchronous with the stimuli presentation. As N400 peaks are associated with encoding and processing semantic information, researchers concluded that synchronizing oscillatory patterns from cognitive and motor sources leads to neural activity entrainment and enhanced memory performance. In a similar study (Schmidt-Kassow et al., 2014), the same research group evaluated the effects of cognitive-motor entrainment on a different physical activity modality, treadmill walking. Participants encoded word pairs, whose presentation was entrained to individual stepping patterns. In the cognitive-motor entrainment condition, participants remembered more words encoded during cognitive-motor entrained treadmill walking than during sedentary sessions.

To understand the underlying modalities of these findings, EEG analyses can also be used to depict how auditory-motor entrainment facilitates attention through neural synchronization. This method has also been tested across a series of studies in which auditory-motor entrainment was hypothesized to narrow attentional processes by creating rhythmic peaks of high and low attentional states. In each study, participants completed an auditory oddball paradigm in which they were asked to respond to incongruent stimuli (Schmidt-Kassow et al., 2013d; Schmidt-Kassow et al., 2019; Schmidt-Kassow et al., 2023). Participants concurrently cycled to the rhythm of the stimuli presentation or sat stationary. EEG data consistently supported the hypotheses as entrained neural activation was seen in larger P300 ERPs (Schmidt-Kassow et al., 2013b) and prestimulus beta-power (Schmidt-Kassow et al., 2023). Moreover, these findings were unique to active synchronization processes and not found in paradigms where participants may have experienced passive Entrainment (Conradi et al., 2016). The researchers suggest these neural changes may contribute to enhanced cognition, particularly memory performance when individuals are presented with a similarly designed auditory-motor paradigm (Schmidt-Kassow et al., 2019).

While entrainment's influence on motor movement quality is less studied compared to its behavioral effects, entrainment may also alleviate increased motor movement variability often associated with dual-task paradigms. Traditional dual-task consequences are often seen in gait destabilization, as revealed through higher CoV measures of swing time (Nankar et al., 2017), stride length (Agostini et al., 2015), and, most commonly, through decreases in overall walking speed (Bayot et al., 2018; Beauchet et al., 2005). However, studies evaluating entrained cognitive-motor dual tasks report inverse results. In an experiment by Schmidt-Kassow et al. (2013b), participants were asked to learn 80 Polish-German vocabulary pairs while sedentary, while cycling, or before a low-intensity cycling session. Those who entrained their cycling pace to auditory stimuli presentation had smaller coefficients of pace variation when compared to traditional dual-task performance *and* retained more word pairs during long-term memory assessments. This experiment suggests that neural entrainment may concomitantly enhance the performance of two separate tasks. However, the small number of experiments on this topic limits the conclusions that can be drawn from their findings. The following section will provide recommendations for further experimentation on the impact of cognitive-motor dual-task entrainment and methodological suggestions to maintain experimental integrity.

## Questions and Future Directions in Cognitive-Motor Entrainment

The current data on cognitive-motor dual-tasking employs many methodologies to explore research questions, resulting in ambiguous conclusions about how conflicting exercise parameters may lead to differential task performance outcomes. In prior work evaluating cognitive-motor entrainment, Schmidt-Kassow and Kaiser (2023) emphasize this point by stating,

> "Future studies should try to clarify whether synchronization was actually the mechanism that led to a narrowed attentional focus, or which other parameters (restricted vs. free motor activity, exercise intensity, motor modality, cognitive processes under investigation) may have contributed to the combined effects. (p. 13)"

The psychological theories discussed previously (i.e., Information Processing Theory, Cognitive Load Theory) predict that physical activities with high attentional demands would deplete neural resources that could be applied to cognitive processes due to limited attentional capacities. Therefore, high-intensity, multi-limb, coordinative, or lengthy physical activities may prevent an individual from reaping potential cognitive benefits. Other factors to consider could include free (overground) movements in heterogeneous environments vs. controlled movements in homogenous environments (such as riding a cycling or rowing ergometer, etc.) and indoor vs. outdoor activities. Most cognitive-motor dual-task reviews report that physical activities with fewer degrees of freedom are more likely to lead to positive benefits (Schmidt-Kassow & Kaiser, 2023). Following these recommendations, low-moderate intensity is recommended over high-intensity physical activity. Indoor-controlled activities are preferred over outdoor, highly-variable activities, such as overground running, and simple, single-limb activities, such as a cycle ergometer, would be preferred over activities requiring limb coordination or postural control, such as running or wall climbing (Lambourne & Tomporowski, 2010; Tomporowski & Qazi, 2020). Prominent researchers have called for further systematic research to clarify these intricacies in the relationship between physical activity and cognition (Lambourne & Tomporowski, 2010; Loprinzi et al., 2018). The same concern should be considered when evaluating cognitive motor entrainment. While research indicates that synchronizing behavioral and motor functions will minimize the amount of neural resources used, alternative factors that increase motor complexity may cancel out or override potential benefits. The methodological design of future studies should consider these factors when determining the type and volume of physical activity that will be incorporated into an entrainment experiment.

The direction and prioritization of entrainment's effects on task outcomes are also unknown. Perhaps neural entrainment's effects on cognition and motor production occur at the same magnitude, or one task type may tend to benefit more than another. In their review of research evaluating the cognitive effects of consecutive motor activity, Schmidt-Kassow and Kaiser (2023) discuss how the specific cognitive tasks and motor modality are also likely to interact. Divergent cognitive processes tend to benefit more from unstructured, free activity, while convergent processes benefit from physical activity that requires minimal attention for execution. Systematic experimentation evaluating different cognitive and motor variables is needed to clarify if there is an interaction between these variables and, if so, what specific properties of entrained cognitive-motor tasks have the greatest potential for success. For example, the principle of entrainment could be applied to an embodied cognition intervention where children play a physical activity game that synchronizes information presentation with stepping, hopping, or jumping (Mavilidi et al., 2021). However, the current research on entrainment does not provide helpful guidelines by which this intervention should be designed. If the ultimate goal of this research is to understand how we can most effectively use entrainment in a real-world setting, understanding if a cognitive or behavioral task will be prioritized over another and how the qualities of other tasks may mediate and treatment effects will help researchers identify scenarios in which neural entrainment has the largest potential for positive outcomes.

Further research clarifying the mechanisms behind entrainment and its neural substrates may also help researchers identify strategies to maximize interventions hoping to harness their cognitive and motor benefits. Techniques that artificially induce entrainment, such as TMS, tACS, or deep brain stimulation, target distinct brain regions and neural networks. Experimentation that compares the efficacy of entrainment's effects within different neural regions and across different cognitive processes or motor outputs would help researchers distinguish which areas within the cortex may be promising candidates for entrainment therapy (Sermon et al., 2023). These evaluations may also identify the pathologies that experience the largest entrainment benefits, increasing the efficiency and impact of the therapeutic application of entrainment moving forward.

Ambiguity across cognitive testing variables further complicates entrainment research. Methodological variation in factors such as stimuli presentation mode and the specific cognitive process studied make it challenging to identify themes across the diverse body of entrainment research. Limited concurrent experimentation prevents researchers from concluding which executive functions or higher-order cognitive processes may reap the largest benefits from entrainment. Reviews on cognitive entrainment alone suggest that attentional processes and memory may be affected more than other cognitive processes (Calderone et al., 2014), but whether this is true for cognitive-motor entrainment paradigms is unknown. Additionally, most cognitive-motor research uses auditory stimulation to evaluate cognitive functioning. However, behavioral and neurobiological psychology tells us that different neural processes are involved in processing visual, auditory, sensory, or kinesthetic information. Visual and kinesthetic stimuli are thought to be easier to remember than auditory stimuli (Bigelow & Poremba, 2014). Perhaps the entrainment of cognitive information is dependent on the sensory modality. Are entrainment benefits more easily identifiable in auditory memory because of the relative challenge of the memory task? Or will larger effects be seen with visual or kinesthetic stimuli presentations?

Individual differences are also likely to influence entrained task performance outcomes. Data from a physio-neuroendocrinological experiment brings forward the idea that individuals with lower cognitive performance abilities at baseline will benefit more from cognitive-motor entrainment (Schmidt-Kassow et al., 2013d). In this study, participants learned 80 Polish-German word pairs and were randomly assigned to one of three learning conditions – cycling before learning, cycling during learning, and seated rest before learning. While participants in both physical activity groups remembered more words at a 48-hour follow-up test, the sedentary group, individuals with lower verbal memory capacity, performed significantly better in the entrained condition alone. Expanding our understanding of how variation in cognitive functioning ability influences the efficacy of a cognitive-motor entrainment paradigm may help researchers identify which subset of the population may benefit the most, allowing them to target their research efforts and develop therapeutic techniques more efficiently and effectively. Age differences may also impact outcomes. A recent meta-analysis reports that physical activity interventions have a larger beneficial impact on children than on adults (Schmid et al., 2023). At the moment, no cognitive-motor entrainment interventions have evaluated cognitive outcomes in a younger population, making this a potential avenue for future research as well.

### *Important Considerations and Limitations*

Because of the limited amount of research on neural entrainment, it can be challenging to experimentally distinguish between true neural entrainment and fluctuations in rhythmic evoked potentials that directly result from stimuli presentation timing (Haegens & Zion Golumbic, 2018). When an individual can anticipate and predict the presentation of stimuli, their sensitivity to the timed stimuli and their ability to tune out noise increases (Auksztulewicz et al., 2019). This phenomenon has caused some researchers to question if the alignment of neural oscillations causes the cognitive benefits reported in studies on neural entrainment or if it is simply due to the predictability of stimuli presentation (Zoefel et al., 2018). Animal studies and clinical studies on humans with atypical neural functioning point towards variation in the activation of distinct subcortical structures to support either theoretical option (Breska & Ivry, 2018). But, experimental studies on a healthy adult population often result in unclear evidence. Bouwer et al. (2020) attempt to delineate the effects between beat-based and memory-based timing of stimuli presentation in their experiment using EEG and behavioral analyses. Both stimuli presentation conditions lead to cognitive enhancements in an auditory detection task. Concurrent EEG analyses suggest that the mechanisms behind behavioral changes result in similar P1 and N1 attenuation as a response to stimuli presentation. However, the neural benefits from the beat-based entrained condition uniquely decreased the detection of out-of-phase noise, providing evidence to support the theorized patterns of fluctuating attention associated with oscillatory entrainment. Further research is needed to clarify if there is a mechanistic distinction between cognitive benefits thought to arise from neural entrainment and temporally predictable stimuli. Enhancing the scientific community's understanding of the neural activities that influence behavior will help elucidate how to leverage these mechanisms to enhance learning and cognitive functioning.

Additional methodological concerns arise when considering the feasibility of confirming neural entrainment through EEG analysis during a cognitive-motor dual task. Traditional EEG practices ask participants to minimize motor production as any muscular activity producing motor output will increase the likelihood of EEG artifacts, decreasing the quality of data reflecting cognitive activity. However, when using EEG to evaluate the cognitive impact of a physical activity intervention in real-time, the methodological designs needed to test proposed hypotheses often require a participant to engage in movement. Though significant developments have been made in the past decade to increase data quality through different pre-processing techniques (Schmidt-Kassow & Kaiser, 2023), researchers should consider how EEG dual-task data may inherently reflect different neural mechanisms than those from the single-task EEG data collected in more traditional neuropsychological experiments.

Most importantly, challenges arise when considering how laboratory data may be translated to a real-world setting so that individuals outside the academic community can realize potential benefits from a cognitive-motor dual-task. While initial studies in controlled environments report cognitive benefits from cognitive-motor entrainment, it is possible that environmental variation could alter the production of motor output and influence anticipated effects. As most entrainment research aims to enhance our understanding of neural entrainment for its beneficial use, the methodological designs of experiments should cater to real-world applications. Cognitive-motor entrainment designs incorporating simple body-weight physical activities are likely to be integrated into a community-based intervention most easily.

Considerations should also be made to ensure participants engage in age-appropriate cognitive-motor tasks to increase the likelihood of an intervention's success.

## Conclusion

Cognitive-motor entrainment research draws from an interdisciplinary network of knowledge stemming from work in psychology, neurology, and kinesiology. Under the appropriate conditions, neural entrainment decreases cognitive effort and attentional demands, enhancing cognitive and motor functioning. This principle can be extended and applied to tasks that require synchronous cognitive and motor output. Research suggests that cognitive-motor entrainment alleviates dual-task costs and enhances cognitive functioning. Further exploration of this principle may allow researchers and practitioners to utilize its benefits and maximize positive outcomes following rehabilitation or learning interventions. For example, this principle may be applied to therapeutic techniques seeking to alleviate the loss of motor skills following a cerebral vascular accident, a classroom-based setting to augment the potential for learning and increase physical activity levels among students, or possibly used as a diagnostic tool to evaluate an individual's ability to manage different levels of cognitive load during task completion. By prioritizing research that seeks to understand how to maximize the benefits of cognitive-motor entrainment, scientists will be able to test its theoretical foundations and determine if this principle holds promise moving forward.

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# CHAPTER 4

# COGNITIVE-MOTOR ENTRAINMENT ENHANCES LONG-TERM EPISODIC MEMORY RETENTION[1]

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# Abstract

In contrast to standard dual-task outcomes, cognitive-motor entrainment has been shown to enhance attentional functionality and auditory long-term memory retention. The present experiments extend this work by evaluating the effects of cognitive-motor entrainment on visual long-term memory retention and variability in motor performance. In experiment 1, participants studied unique 40-word lists under three different learning conditions. When participants learned words in a cognitive-motor entrained condition (words were presented on a screen every fourth stride), they retained more information during free-recall long-term memory assessments when compared to a stationary control ($p < 0.05$). In experiment 2, the same psychological test was administered, but participants were asked to cycle on a stationary ergometer. Similarly, words studied under the entrained dual-task condition (word presentation was matched to cycling patterns) were more easily free-recalled during delayed long-term memory testing than the word lists studied under the traditional dual-task or control condition. In both experiments, no conditional differences were found in relation to recognition memory (accuracy or confidence) or in regard to motor performance quality (gait parameters or cycling cadence). A secondary analysis of the data revealed no significant long-term memory retention differences between the unique physical activity modalities performed in each experiment. Together, these experimental findings suggest that entraining oscillatory patterns of motor production with cognitive stimuli presentation may enhance long-term memory retention and prevent dual-task costs regardless of the mode of physical activity performed. Further research is needed to clarify the exact mechanisms behind these relationships and to translate these laboratory findings into real-world settings.

## Introduction

Researchers have sought to explore the relationship between cognition and physical activity. Scientists report a variety of findings regarding the strength of the association between physical activity and cognition in both children and adults (Audiffren & André, 2019; Berrios Aguayo et al., 2022; Erickson et al., 2019; Hillman et al., 2008; Mavilidi et al., 2022; Morales et al., 2024; Rigdon & Loprinzi, 2019; Wilke et al., 2019).

In the past two decades, evaluating the potential impacts of the physical activity-cognition relationship through acute dual-task experiments has become increasingly popular. Under specific conditions, cognitive-motor dual-tasks (CMDTs) strain the brain's limited neural resources by requiring individuals to perform two tasks concurrently (Leone et al., 2017). Depending on the demands of each task, cognitive or motor components can lead to performance benefits or detriments in isolation; they may also interact with one another to produce one of nine unique performance outcome scenarios (Plummer et al., 2013). Various factors, including an individual's age, psychological or physiological health, and skill level, influence the quality of either task (Huang & Mercer, 2001; Moreira et al., 2021; Schaefer, 2014b; Villarrasa-Sapina et al., 2020). Furthermore, cortical activation patterns, attentional priorities, and neural efficiency during task production significantly impact CMDT outcomes. Prefrontal cortex activation patterns are often associated with positive cognitive-motor dual-task effects, while poor network efficiency and functional connectivity between the prefrontal cortex and sensorimotor areas are correlated to decreased task performance quality (Ding et al., 2024). When a CMDT scenario instigates performance detriments, the resultant decrease in task quality is called dual-task interference (DTi) or dual-task cost (DTC) (Leone et al., 2017).

Two key factors of particular importance to scientists include understanding how acute CMDT scenarios may enhance cognitive performance and how their implementation in traditionally sedentary environments may increase opportunities for physical activity engagement. When studying these notions in young adults, participants are most often asked to walk on a treadmill (Al-Yahya et al., 2011), ride a stationary bike (Schaefer & Schumacher, 2010), or engage in another type of simple continuous physical activity (i.e., ergometer rowing (Duckworth et al., 2021) as they undergo tests of executive function (Bayot et al., 2018) or encode information that will later be evaluated using memory retention tests (Loprinzi et al., 2021a; Tomporowski & Qazi, 2020). Most often, meta-analyses on these topics report that CMDT interventions result in a DTC (Loprinzi et al., 2019a; Qazi et al., 2024). However, a subset of experiments report significant beneficial effects following a CMDT in young adults (Beurskens et al., 2020; Schmidt-Kassow et al., 2013d; Scott et al., 2025).

For example, an experiment by Beurskens et al. (2020) reported positive cognitive outcomes following a CMDT intervention. Participants stood on a stabilometer and performed seven serial three-subtraction assessments for 90 seconds each. Participants who experienced the dual-task conditions improved their cognitive and motor performance quality. Treadmill-walking CMDTs have also been shown to enhance creativity. Oppezzo and Schwartz (2014) evaluated the effects of walking on young adults' creative processing. They found that divergent thinking was significantly better in the dual-task condition compared to a seated single-task control. The authors posit that light-intensity physical activity may cause changes in physiological neural connectivity that boost the mind-body connection and enhance associative memory processes. Similarly, an experiment by Schmidt-Kassow et al. (2013b) in which participants cycled on an ergometer as they listened to sinusoidal tone presentation led to significantly higher attentional processing quality as measured by P300 latency and amplitude than a single-task seated control condition Understandably, the validity of these results are questionable due to small effect sizes, few studies, and inconsistencies in methodological techniques (de Greeff et al., 2018; Donnelly et al., 2016). The variation seen across research suggests that the magnitude and consistency of findings likely depend on the type of psychological outcomes evaluated (Chang et al., 2012; Colcombe & Kramer, 2003; Pontifex et al., 2019).

Following trends in single-task studies that highlight the consistent positive effects of physical activity on memory processes (Qazi et al., 2024; Schmid et al., 2023; Wanner et al., 2020), CMDT studies evaluating long-term memory generally provide the most promising results reflecting increased task performance. For example, Schmidt-Kassow et al. (2014) conducted a treadmill-walking experiment in which young adults learned foreign-language vocabulary words. Participants studied a unique list of words for 30 minutes as they performed light-intensity treadmill walking, in which word presentation occurred on every fourth step, or a single-task condition, in which they sat still on a chair. Memory retention was significantly higher in the dual-task condition compared to the sedentary control condition. A recent systematic replication of this experiment expanded the methodological bounds and outcome variables to evaluate both the memory and motor (gait) outcomes of a CMDT (Scott et al., 2025). Similar to the methods employed by Schmidt-Kassow (2014), auditory word stimuli were presented on every fourth step or randomly as participants walked on a treadmill at their preferred walking speed. Free recall long-term memory tests revealed that conditions in which motor performance and stimuli presentation were consistently aligned resulted in higher memory performance 24 hours following encoding compared to walking during unentrained stimuli presentation and non-walking control conditions. Furthermore, variation across gait phase parameters was lowest in the aligned condition compared to the unentrained dual-task and single-task baseline gait analysis. Similar experimental approaches have been used in an analogous study using ergometer cycling for the motor component of the dual task (Schmidt-Kassow et al., 2013d). In this case, three groups of participants learned 40 foreign word list pairs in one of three 30-minute conditions: after sitting in a canvas chair resting, after cycling, or cycling as they studied the words. In the latter CMDT condition, word presentation aligned with the participants' cycling cadence at 60 RPM. Forty-eight hours later, memory was analyzed using a vocabulary test, and those in the dual-task condition retained more information than those in the sedentary condition.

One similarity among the CMDT long-term memory experiments above stands out – the conditions in which the presentation of auditory stimuli aligned with motor production led to beneficial outcomes compared to a traditional dual-task or a single-task control. Researchers hypothesize that these outcomes can be explained by entrainment theory (Lakatos et al., 2019; Schmid, 2024; Schmidt-Kassow & Kaiser, 2023). Entrainment is an interdisciplinary term referencing the alignment of oscillatory patterns into a single, repetitive *cycle*, distinguishing it from passive synchronization (Bittman, 2021). Entrained neural mechanisms are thought to create a rhythmic context of cortical activation patterns that can align internal information processing systems with efferent or afferent neural signaling (Lakatos et al., 2019). Calderone et al. (2014) propose that the neural activation patterns caused by entrainment enhance the quality of neural functioning through attentional modulation by creating high and low cognitive excitation patterns that align with the presentation of particular external stimulation or preexisting cognitive activity. While further research is necessary to clarify this relationship, entrainment via the efficient use of neural activation patterns likely decreases cortical activity's demand for cognitive resources (Hanslmayr et al., 2019; Large & Snyder, 2009). Research on auditory-motor voluntary entrainment, in which participants voluntarily align their movements with auditory signaling, has revealed promising results in treating motor performance deficiencies (Braun Janzen et al., 2022; Simeon, 2022; Thaut, 2015). These include improving gait quality in children with cerebral palsy (Ghai et al., 2018), young adults who are healthy or who have had a traumatic brain injury  (Alashram et al., 2019; Moumdjian et al., 2018), adults with Multiple Sclerosis, peripheral diabetic neuropathy, Parkinson's disease, and musculoskeletal impairments (Çarıkcı et al., 2021; Conklyn et al., 2010; McIntosh et al., 1997; Suzuki et al., 2019; Thaut et al., 1992), and older adults with late stage dementia or who had experienced a cerebrovascular event (Thaut & Abiru, 2010). Artificially induced entrainment using cortical stimulation has also benefited older adults by stabilizing post-stroke motor actions and improving cognitive output in individuals with dementia (Elyamany et al., 2021; Hsu et al., 2012).

Experiments seeking to understand the neural implications of entrainment theory during a CMDT have identified cortical activation patterns. Cycling studies, in which cognitive stimulation and motor task production align cyclically, have found electroencephalography (EEG) event-related potential (ERP) results that support the mechanistic principles and hypotheses underlying neural entrainment. Researchers have identified larger N400 peaks (Schmidt-Kassow et al., 2010), larger P300 peaks (Schmidt-Kassow et al., 2013b; Schmidt-Kassow et al., 2019), and higher pre-stimulus beta-power (Schmidt-Kassow et al., 2023) when cognitive and motor processes were entrained. These markers are associated with enhanced attention, cognitive processing, and memory functioning, suggesting that coupling oscillatory patterns from cognitive and motor sources enhances cognitive functioning and memory performance (Picton, 1992; Schmidt-Kassow et al., 2010; van Dinteren et al., 2014).

Together, these behavioral and physiological findings highlight how applying entrainment principles to a CMDT may be the key to creating a task in which adults may simultaneously reap psychological and physiological benefits. However, many questions regarding cognitive-motor entrainment remain unanswered. First, most researchers have used auditory stimulation, but less is known about how outcomes might change using alternative sensory input. Visual and kinesthetic stimuli are hypothesized to be more easily remembered than auditory stimuli and may be able to produce larger entrainment effects (Bigelow & Poremba, 2014).

Additionally, while studies have seen cognitive and motor benefits in both cycling and walking physical activity modes, the strength of the relation is unknown. In their review on cognitive-motor dual-tasking, Schmidt-Kassow and Kaiser (2023) suggest that physical activities with fewer degrees of freedom, such as cycling, are more likely to lead to positive benefits than those with more degrees of freedom, such as walking. Further, most cognitive-motor entrainment and memory experiments focus on free-recall memory outcomes and forego alternative analyses such as recognition, prospective, or false memory analyses. In their recent meta-analysis, Qazi et al. (2024) report differential cognitive-motor dual-task results regarding free-recall and recognition memory in particular. In future experiments, measuring both psychological outcomes would permit a parallel comparison between existing memory research and emerging entrainment research.

Based on the experimental findings mentioned above, evaluating cognitive-motor dual-task within the framework of entrainment theory may reveal new insights into particular dual-task scenarios that benefit memory retention and decrease motor performance variation. Therefore, the primary aim of the present experiment was to determine how the timing and predictability of visual word presentation during a motor task influences young adults' long-term episodic free-recall and recognition memory and to evaluate how these outcomes differ as a function of physical activity mode. The methodological design, influenced by Scott et al. (2025) and Schmidt-Kassow et al. (2014), systematically replicated prior studies by altering the type of cognitive stimuli presented and examining the influence of the motor task's mode. Five hypotheses were tested across two experiments. In Experiment 1, participants walked on a treadmill while studying a visual word list. Free recall and recognition memory retention and confidence were predicted to be higher following a cognitive-motor entrainment learning condition than an unentrained dual-task condition and a stationary control (Hypothesis 1). The entrained condition was also expected to have the highest quality motor task production, as measured by the variation across gait assessment parameters (Hypothesis 2). In Experiment 2, participants completed the same cognitive task as Experiment 1, but a cycle ergometer was used for the motor component of the dual task. Free recall and recognition memory retention and confidence were also predicted to be higher following the entrained cycling learning condition when compared to an unentrained dual-task condition and a stationary control (Hypothesis 3). The entrained condition was predicted to produce the lowest Coefficient of Variation during the motor task, as measured by cycling cadence variation (Hypothesis 4). Finally, memory assessment performance was predicted to differ between each experiment due to the motor task modality. Free recall and recognition memory were hypothesized to be higher in Experiment 2's entrained cycling condition when compared to Experiment 1's entrained walking condition (Hypothesis 5).

## Experiment 1: Methodology

### *Study Design, Power Analysis, and Randomization*

A within-subject crossover design assessed participants' long-term memory across three cognitive-motor dual-task conditions. The university's Institutional Review Board approved the experimental design before data collection began. An a priori power analysis calculation (G*Power: F tests, Repeated measures, within factors, Cohen's D of 0.25 (Scott et al., 2025)) resulted in a recommended sample size suggestion of n=24. Because two variables, the experimental condition and the word lists, needed to be controlled, a two-way 3X3 Latin square design was used for randomization. To be conservative and ensure each randomization pattern was distributed equally, the sample size goal was raised to 36.

### *Participants and Recruitment*

Inclusion Criteria: Participants included young adults, 18 to 30 years old, who spoke English as their first language. Individuals were excluded from the study if they (a) were diagnosed with cardiovascular, neuromuscular, musculoskeletal, or rheumatoid disorders; (b) used a major psychoactive medication within the past 12 months (e.g., antidepressants); (c) had a movement disorder or an injury or surgery affecting movement within the past 12 months; (d) were diagnosed with a memory or learning disorder (e.g., ADHD, dyslexia) or balance disorders (e.g., vertigo); (e) were pregnant; or (f) had previously participated in a dual-task research project measuring memory. Because (Schmidt-Kassow et al., 2014) report no sex differences across an entrainment intervention, a convenience sample of men and women was included.

Participants were recruited using flyers, emails, university classroom presentations, and word of mouth. To express interest in the study, individuals completed a Qualtrics survey that confirmed inclusion and exclusion criteria. Participants were compensated $60 in cash for study completion or at a rate of $10/hour in the case of attrition. Participation took about five and a half hours across seven sessions.

### *Surveys and Questionnaires*

A *self-administered medical history questionnaire* and *Godin leisure time physical activity questionnaire* were used to evaluate the participant's readiness to engage in physical activity and gather demographic information (Godin & Shephard, 1985). Participants also completed a *24-hour health history questionnaire* at every session, which tracked sleep, caffeine intake, drug and alcohol consumption, and exercise. If a reported habit exceeded predetermined limits for variation, participants were either asked to wait a day to test again, or their data from that session was thrown out.

### *Word Lists and Memory Tests*

Participants were asked to remember three unique lists of 40 words generated using the following methods used in Loprinzi et al. (2023) and originating from the MRC Psycholinguistic Database (Wilson, 1988). All word lists had mean scores of concreteness, imageability, familiarity, and animation ratings ranging between 480 and 500. The Superlab Psychological software (SuperLab 6, Cedrus) and Stimtracker hardware (Stimtracker Duo., Cedrus) visually presented words at a preprogrammed pace, depending on the learning condition. Words were displayed for 500 ms, with a fixation cross appearing between word presentations. During each condition, participants studied the same list in the same order across two consecutive blocks. At the end of each block, participants repeated as many words as they could remember from the list they had just learned aloud.

Participants learned the three-word lists under different stimuli presentation conditions. In an "entrained" dual-task condition, participants viewed words consistently presented on every fourth stride as they walked on a treadmill. For the unentrained dual-task, words were presented randomly (every 2nd, 3rd, 4th, 5th, or 6th stride that averaged to occur every four strides) as participants walked on the treadmill. Finally, in a single-task "control" condition, participants stood stationary on a treadmill as they viewed words presented words with the same timing as the unentrained condition.

Long-term memory was assessed using free recall and recognition memory tests. Free recall assessments required participants to state as many words as they could remember from a list aloud without any cues. Verbal responses were auditorily recorded and played back following the testing session to increase data collection accuracy. During recognition memory assessments, participants viewed a slideshow randomly displaying all 40 words from the relevant list and 40 distractor words and used a response pad to indicate "yes" they had or "no" they had not studied the word displayed and their confidence in this answer as "high," "moderate," or "low" following recommendations from Yonelinas et al. (1996). Recognition was assessed using Signal Detection Theory (Green & Swets, 1966), with the value A' calculated to analyze the relation between hits and false alarms via the following formula $A' = \frac{1}{2} + (\frac{(y-x)(1+y-x)}{4y(1-x)})$ where $x = \frac{false\ alarms}{distractor\ words}$ and $y = \frac{hits}{List\ A\ words}$. While relative recognition memory confidence would traditionally be analyzed with a receiver operating curve, the small amount of data per participant negated this option's validity and reliability (Yonelinas & Parks, 2007).

### *Physiological Measurements and Physical Activity Equipment*

During all physical activity, participants wore chest-mounted heart rate monitors (Polar, Model 0537) and intermittently reported their rating of perceived exertion (RPE) from Borg's 6-20 RPE scale (Borg, 1998). Gait was assessed during treadmill (Cybex, 770T) walking using insole pressure transducers (Ultium Insole SmartLeads, NORAXON) that transmit gait data to an analytic software (myoResearch, NORAXON). Insoles were placed in lab-provided zero-drop shoes. A force-sensitive resistor (BioPac, TSD 111A) was also worn on the right foot, which responded to the foot's heel strike phase of the gait cycle. This signal was transmitted using a BioPac system (Biopac MP150) to the hardware (Stimtracker Duo., Cedrus) and software (SuperLab 6, Cedrus) used for stimuli presentation.

## Experiment 1: Procedures

All seven testing sessions started with a 24-hour history questionnaire and were scheduled at the same time of day (+/- 1 hour) to decrease external error.

Participants performed a visual-motor dual-task during treadmill walking. In session 1, participants first signed consent forms and completed questionnaires (self-administered medical history, 24-hour health history, and Godin leisure-time exercise. Researchers then evaluated demographic characteristics (resting heart rate, height, and weight) before guiding participants through a baseline long-term memory assessment (Hale et al., 2019) and a walking speed protocol to determine their preferred treadmill pace used in the following sessions. (See Appendix D for further details.) Because moderate-light physical activity is preferable in cognitive-motor dual-task conditions, participants were excluded from the study if they selected a pace over three mph (Tomporowski & Qazi, 2020). At the end of the session, a five-minute baseline gait assessment was collected at the established preferred pace. Up to 62 hours were permitted to elapse before the start of session two. The following sessions, two and three, four and five, and six and seven, were differentiated based on the assigned world-learning condition: entrained, unentrained, and control.

On even numbered session days, participants warmed up on a treadmill at their preferred pace for 3 minutes before studying a word list under three possible experimental conditions. In the entrained condition, motor performance was entrained to cognitive stimuli presentation by presenting words on every 4th stride. In the unentrained condition, words were presented during walking on random strides (2nd, 3rd, 4th, 5th, or 6th) that averaged to occur every four strides. In the control condition, participants stood still on the treadmill as words were displayed following the unentrained condition's presentation pattern. In pilot testing and a very similar experiment, the average time per stride was 1500 ms (Scott et al., 2025). Therefore, this time was used to calculate the different delays needed in the control condition. This process ensured that the study time across all learning conditions was relatively equivalent. After the word learning task, the participant completed a 3-minute Digit Cancellation Task (DCAT) to prevent rehearsal before a long-term memory free-recall assessment (Hatta et al., 2012). They then sat quietly for 10 minutes before a final free-recall memory assessment.

Odd numbered session days were used as a 24-hour follow-up to assess long-term memory retention. Participants completed a free recall test followed by a recognition test. The seventh session also included a debrief discussion and compensation. Sessions three and four, as well as five and six, were separated by 24 or 48 hours.

## Experiment 1: Results

### *Participants and Enrollment*

Altogether, 126 people completed the Qualtrics survey expressing interest in Experiment 1 (126). Thirty-nine participants enrolled to participate, but three did not complete the study or were excluded from the analysis due to errors or non-compliance with methodological procedures. Therefore, data from 36 participants were analyzed. (See Table 4.4 for demographic information.)

### *Data preparation*

Before statistical analyses were completed in SPSS, data were cleaned using a median absolute deviation (MAD) method (Leys et al., 2013). This method uses the formula $MAD = b * M_i(|x_i - M_j(x_j)|)$ in which M represents the median, x represents each data point, and b = 1.4826 as a constant tied to assumed normality of the data points when outliers are excluded (Rousseeuw & Croux, 1993). A threshold of 2 was set; the decision criteria adhered to the following formula $\frac{x_i - M}{MAD} > |\pm 2|$.

Memory data was analyzed to ensure there were no session order (E1 p = 0.77) or word list effects (E1 p = 0.13) influencing overall findings. Gait data were converted to a coefficient of variation (CoV= (SD/mean)*100) to analyze the variability in motor output. All DCATs were graded following Hatta et al.'s (2012) guidelines to calculate the outcome variables: Total Performance, Odds Ratio, and Reduction Ratio.

*Memory Outcomes*

Long-term free-recall memory scores from the immediate, 10-minute, and 24-hour testing time points were analyzed using 3(time)X3(condition) repeated measures ANOVA. The results revealed a significant main effect of time (sphericity violation p = 0.006, Greehouse-Geisser $F(2,70)= 65.87$, $p < 0.001$, $\eta_p^2 = 0.65$) and condition ($F(2,70)= 3.63$, $p = 0.03$, $\eta_p^2 = 0.10$) but no time*condition interaction ($F(4,140)= 1.73$, $p = 0.14$, $\eta_p^2= 0.05$). Simple pairwise comparisons identified time differences between immediate to 10-minute recall ($p = 0.005$), immediate to 24-hour recall ($p < 0.001$), and 10-minute to 24-hour recall ($p < 0.001$), and conditional differences between the entrained and the control condition ($p = 0.005$). There were no conditional differences in recognition long-term memory performance as measured by A' ($F(2, 70) = 2.53$, $p = 0.09$, $\eta_p^2 = 0.067$) or confidence ($F(2, 70) = 0.44$, $p = 0.64$, $\eta_p^2 = 0.012$).

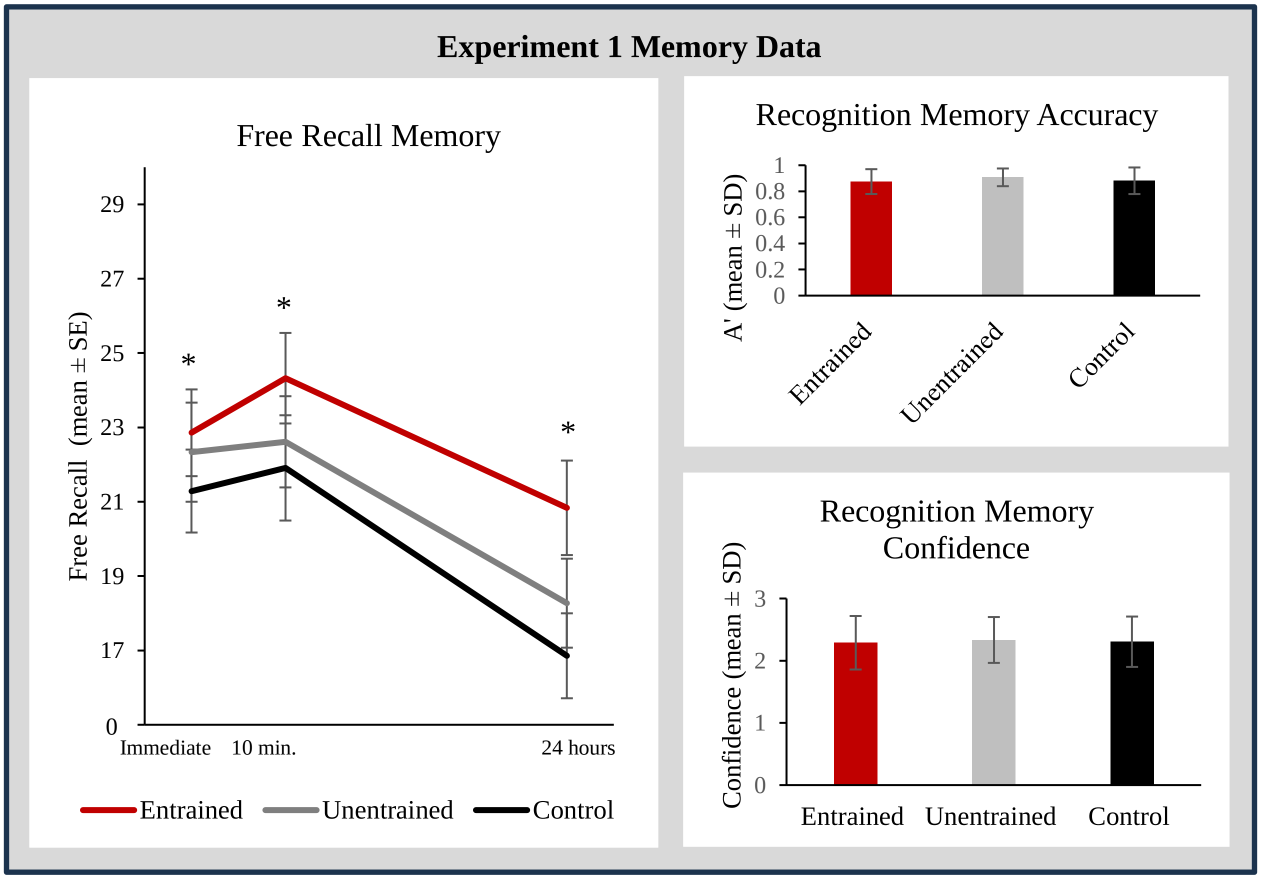
**Experiment 1 Memory Data**

**Figure 4.1 Experiment 1 Memory Data**

The number of words free-recalled in the entrained conditions was significantly higher than the control condition at every time point. An asterisk (*) indicated a p-value < 0.05. There was no difference between the unentrained and the entrained or control conditions or in recognition memory confidence or accuracy scores.

### *Physiological Outcomes*

The average participants' preferred walking speed was 2 ± 0.4 mph. Two repeated measures ANOVAs analyzing the 3-minute warm-up found no differences across conditions in participants' heart rates (sphericity violation $p = 0.003$, Greenhouse-Geisser correction $F(1.55, 54.20) = 1.30$, $p = 0.27$, $\eta_p^2 = 0.04$) or RPE (sphericity violation $p = 0.04$, Greenhouse-Geisser correction $F(1.71,59.73) = 1.27$, $p = 0.28$, $\eta_p^2 = 0.03$). A 3(condition)X2(block) repeated measure ANOVA heart rate during the intervention identified a main effect for condition ($F(2,70) = 6.73$, $p = 0.002$, $\eta_p^2 = 0.16$) but no main effect of time (block) ($F(1,35) = 0.64$, $p = 0.43$, $\eta_p^2 = 0.02$). Simple comparisons revealed differences between the control and entrained conditions ($p = 0.002$) and the unentrained conditions ($p = 0.002$) but no difference between the entrained and unentrained conditions ($p = 0.91$). Repeated measures ANOVAs also found no conditional differences in DCAT attention scores ($F(2, 34) = 0.42$, $p = 0.41$, $\eta_p^2 = 0.05$).

| **Table 4.1** | N | Mean | Standard Deviation |
|---|---|---|---|
| Stance Phase % | 142 | 63.17 | 3.38 |
| Load Response % | 137 | 13.83 | 5.68 |
| Single Support % | 140 | 34.39 | 34.39 |
| Pre-swing % | 135 | 14.94 | 17.37 |
| Swing Phase % | 143 | 36.82 | 3.36 |
| Double Stance % | 137 | 27.80 | 10.25 |
| Step Time (ms) | 142 | 880.57 | 1177.50 |
| Stride Time (ms) | 147 | 1266.69 | 169.12 |
| Cadence (ms) | 143 | 96.80 | 12.11 |

**Table 4.1** Average Gait Data Across Conditions

The average values for each gait parameter across all conditions are displayed. The raw values reflected in this table align with expected gait cycle proportions and spatiotemporal parameters in healthy young adults (Rössler et al., 2024). *Parameters reported using a percentage reflect the proportion of time each parameter used compared to the time of completing a full gait cycle.

Equipment errors during data collection resulted in some missing gait data (Table 4.1). This issue led to the completion of a mixed linear model analysis to avoid excessive data imputation. A series of nine restricted maximum likelihood fixed effect analyses were completed for each gait parameter. No differences were found when the entrained, unentrained, and baseline gait measurements were compared. See Tables 4.1 and 4.2 for further information.

## Experiment 1: Brief Discussion

Experiment 1's visual long-term memory results affirm the initial hypothesis and parallel auditory long-term memory outcomes from previous experiments aligning cognitive stimulation with motor production (Schmid, 2024; Schmidt-Kassow et al., 2013a; Schmidt-Kassow et al., 2014; Scott et al., 2025). However, the methodological design of prior experiments prevents the comparison of results across different modes of motor production. It is possible that altering the degrees of freedom included in a CMDT could alter long-term memory retention or the variation in motor task production (Schmid, 2024; Schmidt-Kassow & Kaiser, 2023; Tomporowski & Qazi, 2020). Therefore, a systematic replication of experiment one was conducted using cycling as the motor task. Measures were taken to ensure the same visual stimuli long-term memory analysis was used and that physical activity engagement remained at a light intensity to match that of Experiment 1.

**Table 4.2 Average Gait CoV Data by Condition and Block (next page)**

The analysis of all gait data using the Coefficient of Variation (CoV) to reflect inconsistencies in gait patterns across nine parameters. No significant differences were found across conditions, blocks, or conditionXblock interaction.

| **Table 4.2** | Baseline | Entrained Block 1 | Entrained Block 2 | Unentrained Block 1 | Unentrained Block 2 | Mixed Modelling Tests of Fixed Effects | | |
|---|---|---|---|---|---|---|---|---|
| | Mean ± SD | Mean ± SD | Mean ± SD | Mean ± SD | Mean ± SD | Condition | Block | Condition*Block |
| *Stance Phase %* | 4.31 ± 2.63 | 3.89 ± 5.41 | 3.98 ± 5.02 | 3.00 ± 2.40 | 1.94 ± 0.98 | F(2,1) = 2.30,<br>p = 0.10 | F(1,1) = 0.43,<br>p = 0.51 | F(1,1) = 0.61,<br>p = 0.44 |
| *Load Response %* | 8.26 ± 4.16 | 7.72 ± 5.05 | 7.75 ± 6.91 | 13.9 ± 21.7 | 7.62 ± 4.54 | F(2,1) = 1.67,<br>p = 0.19 | F(1,1) = 2.31,<br>p = 0.13 | F(1,1) = 2.35,<br>p = 0.13 |
| *Single Support %* | 5.74 ± 7.34 | 4.13 ± 3.07 | 4.33 ± 3.35 | 8.75 ± 24.3 | 4.24± 3.64 | F(2,1) = 0.58,<br>p = 0.56 | F(1,1) = 0.99,<br>p = 0.32 | F(1,1) = 1.18,<br>p = 0.28 |
| *Pre-Swing %* | 9.04 ± 7.38 | 8.17 ± 5.20 | 6.59 ± 2.44 | 11.56 ± 18.10 | 7.90 ± 5.10 | F(2,1) = 0.91,<br>p = 0.41 | F(1,1) = 2.08,<br>p = 0.15 | F(1,1) = 0.33<br>p = 0.57 |
| *Swing-Phase %* | 4.39 ± 3.14 | 4.40 ± 3.92 | 3.80 ± 2.32 | 5.47 ± 6.41 | 3.45 ± 1.99 | F(2,1) = 0.32,<br>p = 0.72 | F(2,1) = 3.15,<br>p = 0.08 | F(2,1) = 0.93,<br>p = 0.34 |
| *Double stance %* | 6.13 ± 3.13 | 6.01 ± 4.73 | 5.15 ± 2.31 | 9.30 ± 13.17 | 9.84 ± 19.86 | F(2,1) = 1.97,<br>p = 0.14 | F(2,1) = 0.01,<br>p = 0.92 | F(2,1) = 0.12,<br>p = 0.73 |
| *Step Time (ms)* | 4.17 ± 2.68 | 5.46 ± 7.05 | 3.60 ± 1.94 | 6.88 ± 16.30 | 3.38 ± 1.69 | F(2,1) = 0.75,<br>p = 0.47 | F(2,1) = 3.15,<br>p = 0.08 | F(2,1) = 0.29,<br>p = 0.59 |
| *Stride Time (ms)* | 3.75 ± 3.41 | 4.28 ± 5.65 | 4.25 ± 5.12 | 5.68 ± 17.59 | 2.50 ± 1.38 | F(2,1) = 0.24,<br>p = 0.78 | F(2,1) = 1.03,<br>p = 0.31 | F(2,1) = 1.00,<br>p = 0.32 |
| *Cadence (ms)* | 3.44 ± 2.45 | 2.68 ± 1.84 | 2.86 ± 2.08 | 3.88 ± 7.51 | 2.36 ± 1.09 | F(2,1) = 0.15,<br>p = 0.86 | F(2,1) = 0.89,<br>p = 0.35 | F(2,1) = 1.46,<br>p = 0.23 |

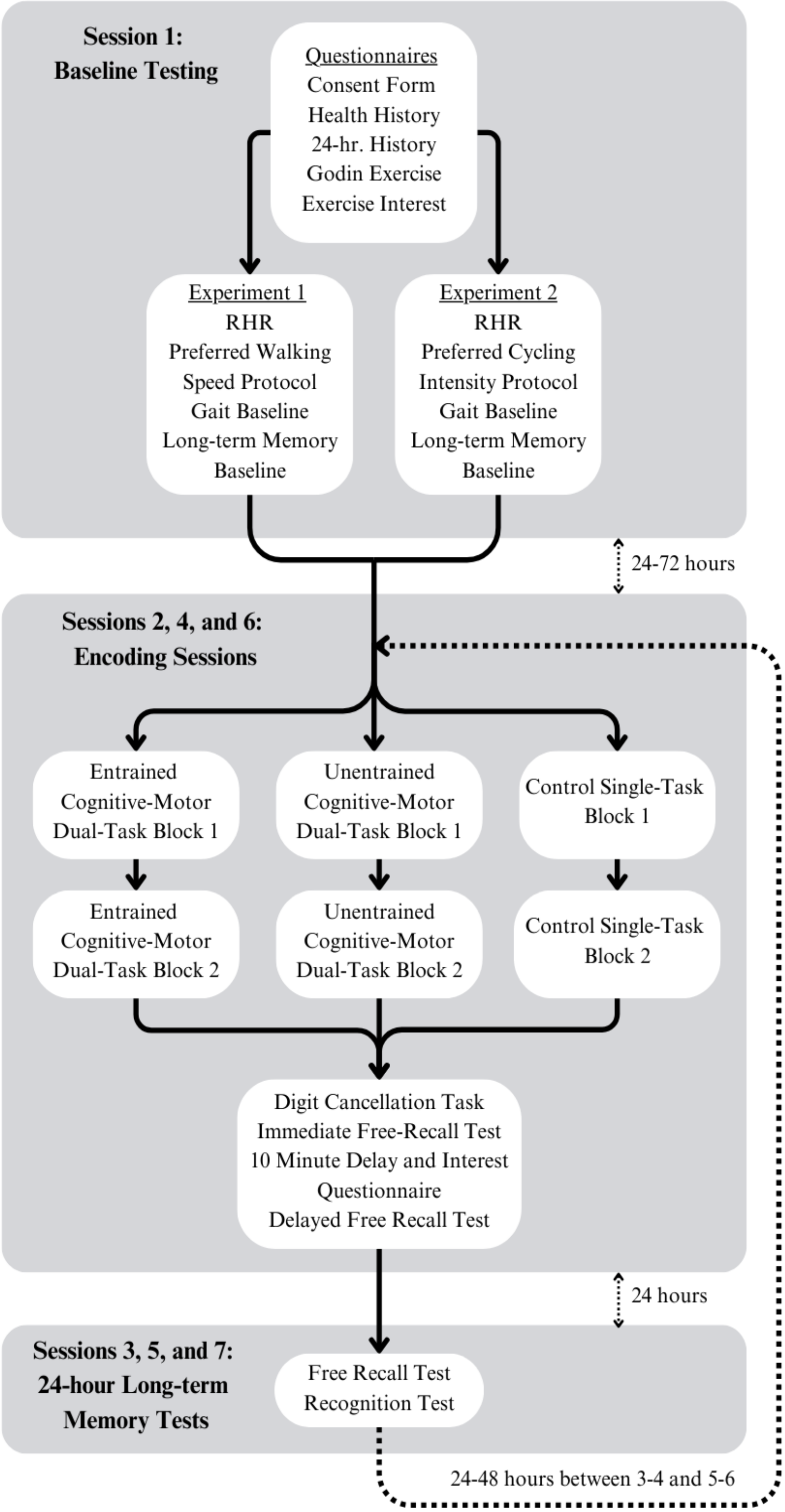

**Figure 4.2**

Methodological Flow Chart of Experimental Procedures – While not displayed, note the physical activity modality differences during the encoding sessions in which participants in Experiment 1 walked on a treadmill and those in Experiment 2 rode on a cycling ergometer.

## Experiment 2: Methodology

### *Study Design, Power Analysis, and Randomization*

In Experiment 2, protocols and psychological testing procedures mimicked Experiment 1, which used a within-subject crossover design to assess participants' long-term memory across three cognitive-motor dual-task conditions. However, Experiment 2 used ergometer cycling instead of treadmill walking for the motor component. The same a-priori power analysis from Experiment 1 was used to calculate the sample size goal for Experiment 2 of 36 participants.

### *Participants and Recruitment*

The inclusion and exclusion criteria from Experiment 1 were also used for Experiment 2. Please refer to the sections above for these details. Following Institutional Review Board approval, participants were recruited using flyers, emails, university classroom presentations, and word of mouth. Participants were compensated $60 in cash for study completion or at a rate of $10/hour in the case of attrition. Participation took about five and a half hours across seven sessions.

### *Surveys and Questionnaires*

All surveys and questionnaires used for Experiment 2 matched those from Experiment 1.

### *Word Lists and Memory Tests*

Participants were asked to remember the same three unique lists of 40 words from Experiment 1. The Superlab Psychological software (SuperLab 6, Cedrus) and Stimtracker hardware (Stimtracker Duo., Cedrus) visually presented words for 500 ms at a preprogrammed pace. All participants studied the same list in the same order across two consecutive blocks and then repeated aloud as many words as they could remember from the list.

Participants learned the three-word lists under different stimuli presentation conditions. In the entrained condition, motor performance was entrained to cognitive stimuli presentation by presenting words on every sixth pedal rotation (6000 ms). Assuming participants maintained a 60 RPM pace, this procedure allowed the time between word presentations in Experiment 1 and 2's entrained conditions to be equivalent (average stride time in Experiment 1: 1500 ms X 4 strides = 6000 ms). The same 1500 ms time interval was used to calculate the unentrained presentation pattern for the unentrained cycling and stationary control conditions. Following the random presentation pattern from Experiment 1, words were presented at a non-constant rate that averaged to every 6000 ms. Therefore, stimuli presentation ranged from 3000 to 9000 ms in 1500 ms intervals.

All procedures following the word learning task on sessions two, four, and six and all 24-hour follow-up testing matched those from Experiment 1. Participants studied and repeated back each word list aloud twice during encoding. Next, after completing a 3-minute D-CAT attention test, participants immediately free-recalled the words studied and finally repeated this step following a 10-minute delay.

Long-term memory was assessed using free recall and recognition memory tests following the same procedures as Experiment 1. Free recall assessments required participants to state as many words as they could remember from a list aloud, and recognition memory tests required participants to select the words they recognized amongst a slideshow of distractors and indicate their confidence in this answer.

### *Physiological Measurements and Physical Activity Equipment*

During cycling, participants wore chest-mounted heart rate monitors (Polar, Model 0537) and intermittently reported their rating of perceived exertion (RPE) from Borg's 6-20 RPE scale (Borg, 1998). Participants cycled on a stationary ergometer (Lode, Excalibur Sport 3000 W Ergometer) with a cadence sensor fixed to the right crank arm (RPM Cycling Sensor Bundle, Wahoo Fitness). The cadence sensor recorded the average cadence every second during the baseline cadence assessment and the entrained and unentrained encoding trials.

## Experiment 2: Procedures

All seven testing sessions started with a 24-hour history questionnaire and were scheduled at the same time of day (+/- 1 hour) to decrease external error. In session 1, participants signed consent forms and completed questionnaires (self-administered medical history, 24-hour health history, and Godin leisure-time exercise). Demographic data (resting heart rate, height, and weight) and baseline long-term memory capabilities (Hale et al., 2019) were also initially collected.

Next, participants completed a cycling familiarization protocol. During this protocol, participants cycled to a metronome playing at a rate of 60 RPM and established intensity based on RPE, following Schmidt-Kassow et al.'s (2013d) protocol. They were blinded to the resistance set on the bike and asked to report their RPE across a range of cycling intensities. The goal was to establish the average resistance at which the individual reached an RPE of 9. 9 was selected as the target RPE because this was the average RPE from Experiment 1 and ensured physical activity remained at a light intensity. To see a detailed explanation of this process, reference Appendix D. The average cycle ergometer resistance, calculated from the three familiarization trials, was used throughout Experiment 2, including the final measurement of session 1, a 5-minute baseline cadence assessment. Up to 62 hours were permitted to elapse before the start of session two.

The following sessions, two and three, four and five, and six and seven, were grouped by condition. On even session days, participants warmed up on the ergometer at their preferred wattage for 3 minutes before studying a word list under the same three experimental conditions. During the warm-up and 30 seconds before the start of both word learning blocks, a 60 bpm metronome was played. Participants were asked to cycle at the metronome's pace and maintain the pace as best they could once the trial started, following the procedure of similar cycling studies (Schmidt-Kassow et al., 2019; Yang & Wu, 2017). In the entrained condition, motor performance was entrained to cognitive stimuli presentation by presenting words on every 6th pedal rotation (6000 ms). In the unentrained condition, words were presented at a non-constant rate that averaged to every 6000 ms as participants were cycling. Stimuli presentation ranged from 3000 to 9000 ms but always coincided with the completion of a pedal rotation at a rhythm of 60 RPM. In the control condition, word presentation was the same as in the unentrained condition, as the participant sat stationary on the ergometer.

At the end of each trial, participants repeated as many words as they could remember. When the trials finished, participants completed a 3-minute D-CAT attention test to prevent rehearsal immediately before completing another free recall session. Following a 10-minute quiet break, they completed another free word list recall to end the session.

On odd-numbered 24-hour follow-up session days, participants completed a free recall memory assessment and a recognition memory test.

## Experiment 2: Results

### *Participants and Enrollment*

One hundred forty-four people expressed interest in the study through a Qualtrics survey. Ultimately, 39 participants enrolled. After two were excluded for non-compliance with methodological procedures and one dropped out, 36 participants' data were ultimately analyzed.

### *Data preparation*

All DCATs were graded following Hatta et al.'s (2012) guidelines and formulas to calculate three outcome variables: Total Performance, Odds Ratio, and Reduction Ratio.

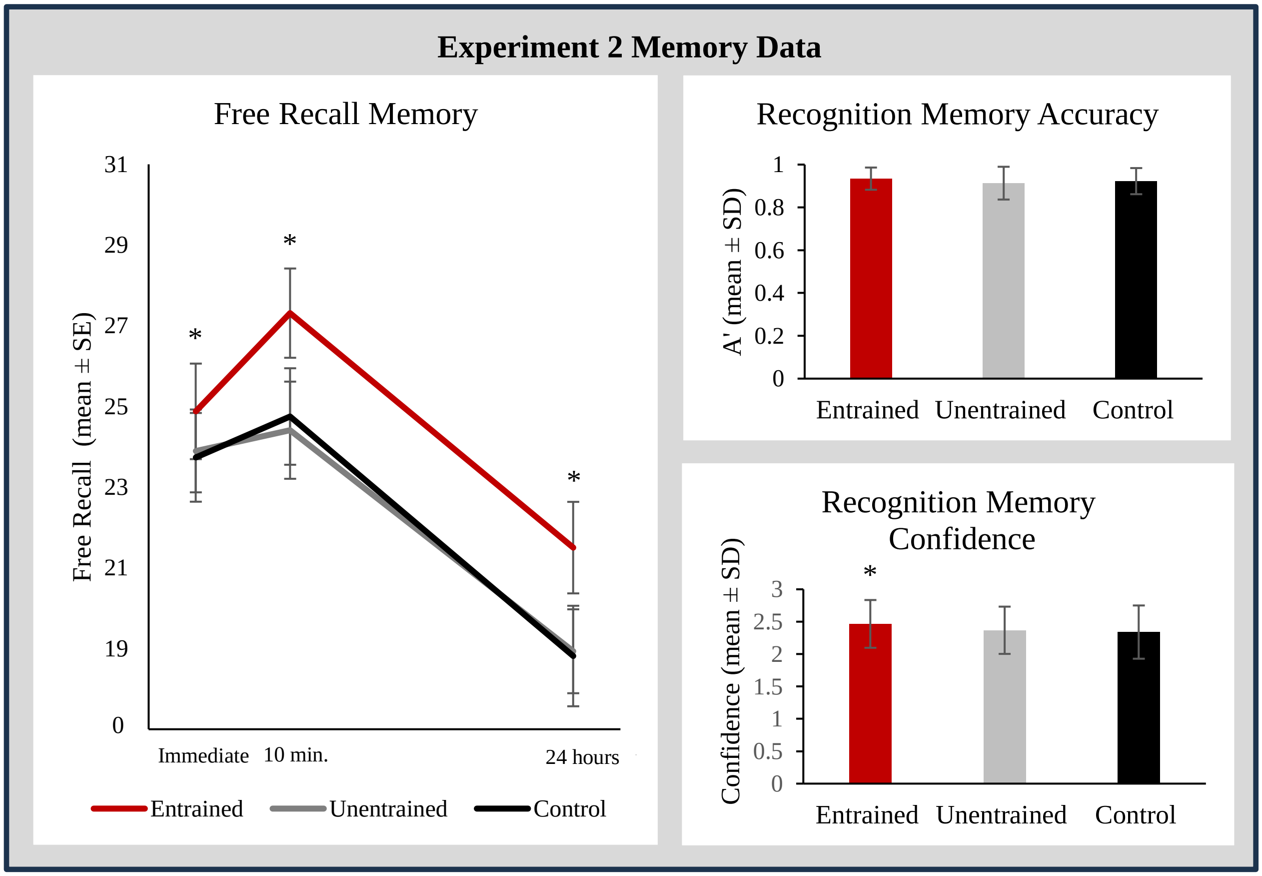

**Figure 4.3 Experiment 2 Memory Data**

Words free recalled in the entrained conditions were significantly higher than both the unentrained and control conditions at every time point (* = p < 0.05). Experiment 2's recognition memory confidence figure further indicates a significant difference across conditions. Participants reported a higher level of confidence in their recognition memory responses in the entrained condition (2.47 ± 0.37) when compared to the unentrained (2.37 ± 0.37) and control (2.34 ± 0.42) conditions. In contrast, there were no differences found across the entrained (2.29 ± 0.44), unentrained (2.33 ± 0.37), or control (2.30 ± 0.41) conditions in Experiment 1.

*Memory Outcomes*

Experiment 2's long-term free-recall memory results were analyzed using a 3(time)X3(condition) repeated measures ANOVA and found significant main effect of time ($F(2,70)= 94.07$, $p < 0.001$, $\eta_p^2 = 0.73$) and condition ($F(2,70)= 3.87$, $p = 0.03$, $\eta_p^2 = 0.10$) but no time*condition interaction ($F(4,140) = 0.95$, $p = 0.14$, $\eta_p^2 = 0.03$). Simple pairwise comparisons identified time differences between immediate to 10-minute recall ($p = 0.001$), immediate to 24-hour recall ($p < 0.001$), and 10-minute to 24-hour recall ($p < 0.001$), and condition differences between the entrained and both the unentrained ($p = 0.03$) and the control condition ($p = 0.009$). Recognition memory data were analyzed using one-way repeated measures ANOVAs. There were no conditional differences in recognition memory as measured by A' (violated sphericity ($p=0.07$), Greenhouse Geiser correction $F(1.74,60.98) = 2.64$, $p = 0.09$; $\eta_p^2 = 0.07$). However, there was a significant conditional difference in confidence ($F(2,70) = 4.24$, $p = 0.018$; $\eta_p^2 = 0.11$). Pairwise comparisons revealed that confidence reported during recognition memory tests for the entrained condition was greater than the unentrained ($p = 0.017$) and the control condition ($p = 0.016$).

*Physiological Outcomes*

On average, participants cycled with 24.14 ± 12.7 watts of resistance. Heart rate ($F(2,70) = 1.16$, $p = 0.32$, $\eta_p^2 = 0.036$) and RPE ($F(2,70) = 0.72$, $p = 0.49$ $\eta_p^2 = 0.02$) were stable across conditions during the 3-minute warm-up. During the intervention, there was no main heart rate effect for block ($F(1,35) = 0.04$, $p = 0.85$, $\eta_p^2 = 0.001$), but there was a main effect for condition ($F(2,70) = 26.50$, $p < 0.001$, $\eta_p^2 = 0.43$). Simple comparisons revealed differences between the control and entrained conditions ($p < 0.001$) and the unentrained conditions ($p < 0.001$) but no difference between the entrained and unentrained conditions ($p = 0.5$).

| | Mean CoVs ± SD |
|---|---|
| Baseline Ergometer Cycling | 7.15 ± 4.50 |
| Entrained Ergometer Cycling Trial 1 | 5.33 ± 3.21 |
| Entrained Ergometer Cycling Trial 2 | 6.21 ± 4.77 |
| Unentrained Ergometer Cycling Trial 1 | 4.51 ± 3.03 |
| Unentrained Ergometer Cycling Trial 2 | 7.16 ± 3.97 |

**Table 4.3** Cycling Ergometer Data Across Conditions and Trials

All cycling analyses followed the same mixed model analysis procedures and setting as the gait analysis mentioned above to maintain consistency in data analysis. A Mixed Model analysis of cycling CoV revealed a main effect of condition ($F(1,2) = 4.14$, $p = 0.018$) and block ($F(1,1) = 8.19$, $p = 0.005$) but no interaction effect ($F(1,1) = 1.84$, $p = 0.18$). Simple pairwise comparisons could not identify what underlying relationships between conditions drove the effect. A near significant difference ($p = 0.060$) between blocks 1 and 2 and a mean difference of -1.057 suggests that CoV in block 1 tended to be lower than block 2.

A one-way repeated measures ANOVA identified no differences across cycling conditions regarding DCAT attention test scores (F(2, 34) = 0.41, p = 0.66, $\eta_p^2 = 0.02$).

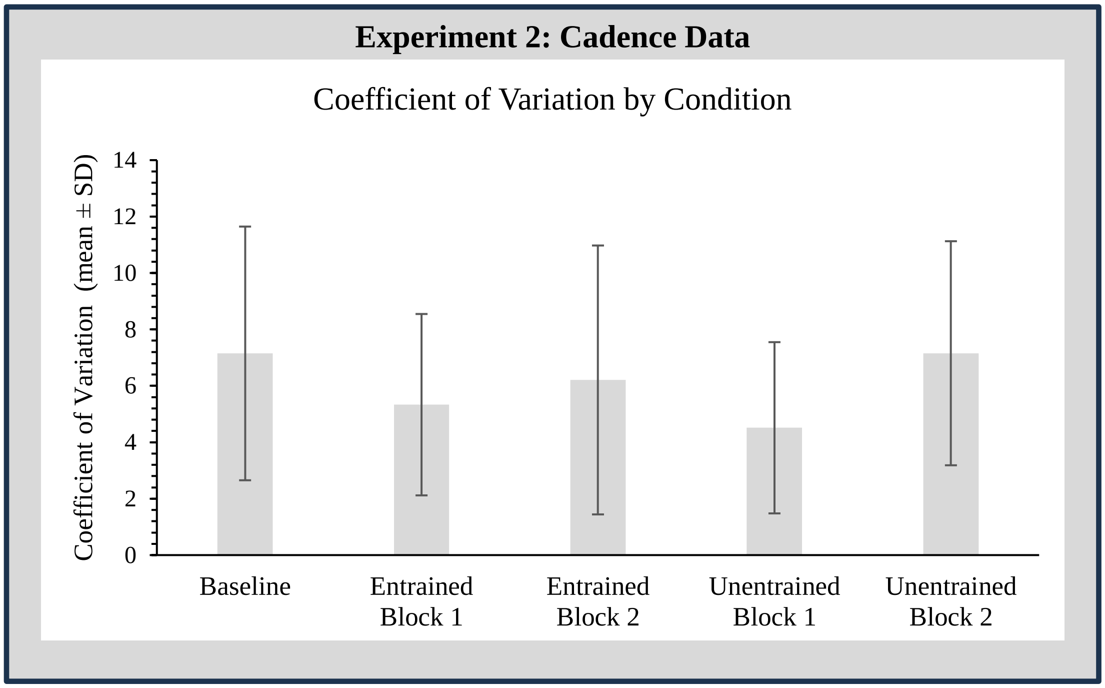

**Figure 4.4 Cadence CoV Data –** No significant differences were found.

| | Experiment 1 | Experiment 2 | t-test |
|---|---|---|---|
| Age (years) | 21.0 ± 2.9 | 21.5 ± 1.9 | t = -0.66, p = 0.08 |
| Sex (%F) | 64% | 75% | t = 1.02, p = 0.05* |
| Height (cm) | 171.7 ± 8.1 | 169.2 ± 7.7 | t = 1.08, p = 0.42 |
| Weight (kg) | 68.4 ± 14.2 | 66.5 ± 11.6 | t = 0.55, p = 0.90 |
| Resting Heart Rate (bpm) | 65.3 ± 8.4 | 67.0 ± 7.8 | t = 0.55, p = 0.97 |
| Godin Leisure Time Exercise Score | 42.4 ± 22.9 | 39.0 ± 26.0 | t = 0.13, p = 0.19 |

**Table 4.4 Demographic Data** (mean ± SD)

## Experiment 1 and Experiment 2 Modality Comparisons

### *Participants and Enrollment*

Demographic data significantly differed only in relation to the number of female participants ($p = 0.05$). Experiment 2 included four more female participants than Experiment 1.

### *Memory Outcomes Modality Comparison*

Long-term free-recall memory across both experiments was analyzed using a 2(mode)X3(time)X3(condition) repeated measures ANOVA. Because Box's Test of Equality of Covariance Matrices was violated, ($p = 0.05$) Pillai's Trace output was used to identify main effects of time ($F(2,69) = 120.65$, $p < 0.001$, $\eta_p^2 = 0.78$) and condition ($F(2,69) = 8.12$, $p < 0.001$, $\eta_p^2 = 0.19$) but no overall difference across modes ($F(1,70)= 1.73$, $p = 0.19$, $\eta_p^2 = 0.02$). A secondary 2(mode)X3(time) comparison of the entrained condition was run due to the original hypothesis predicting differences in this particular learning condition. However, while there was an effect of time (sphericity violation $p = 0.05$, Greenhouse-Geiser corrections: $F(1.84,129.08) = 36.82$, $p < 0.001$, $\eta_p^2 = 0.34$), none was found for mode ($F(1,70) = 1.41$, $p = 0.23$, $\eta_p^2 = 0.02$). The same analysis produced parallel results for the unentrained (sphericity violation $p = 0.014$, Greenhouse-Geiser corrections: time $F(1.79,125.49) = 56.94$, $p < 0.001$, $\eta_p^2 = 0.45$; mode ($F(1,70) = 0.57$, $p = 0.45$, $\eta_p^2 = 0.008$) and the control condition (sphericity violation $p = 0.035$, Greenhouse-Geiser corrections: time $F(1.83,128.15) = 56.66$, $p < 0.001$, $\eta_p^2 = 0.45$), none was found for mode ($F(1,70) = 2.26$, $p = 0.14$, $\eta_p^2 = 0.03$).

Additional 2(mode)X3(condition) ANOVAs were run at each time point. The immediate free recall established that participants from Experiments 1 and 2 had equivalent foundational memory abilities with no main effects of mode (F(1,70) = 1.99, p = 0.16, $\eta_p^2 = 0.03$) or condition (F(2,140) = 1.51, p = 0.22, $\eta_p^2 = 0.02$). 10-minute free recall analyses identified a main effect of condition (F(2,140) = 5.53, p = 0.005, $\eta_p^2 = 0.07$) but not mode (F(1,70) = 1.99, p = 0.12, $\eta_p^2 = 0.03$). 24-hour free recall results followed suit with a main effect of condition (F(2,140) = 18.89, $p < 0.001$, $\eta_p^2 = 0.11$) but no effect of mode (F(1,70) = 1.99, p = 0.42, $\eta_p^2 = 0.009$). In both cases, simple planned comparisons reveal that the entrained condition outperformed the unentrained (10 minutes: p = 0.023, mean difference = 2.1 words; 24 hours: p = 0.005, mean difference = 2.6 words) and the control conditions (10 minutes: $p < 0.001$, mean difference = 2.5 words; 24 hours: $p < 0.001$, mean difference = 3.4 words). The unentrained and control conditions did not significantly differ at any time point (10 minutes: p = 0.61; 24 hours: p = 0.34).

| | Immediate Free Recall | 10-minute Free Recall | 24-hour Free Recall | Recognition A' |
|---|---|---|---|---|
| All Treadmill Walking | 22.16 ± 7.31 | 22.95 ± 7.84 | 18.65 ± 7.44 | 0.89 ± 0.09 |
| All Ergometer Cycling | 24.17 ± 6.68 | 25.50 ± 7.17 | 19.75 ± 7.00 | 0.93 ± 0.06 |
| Entrained Treadmill Walking | 22.85 ± 7.0 | 24.32 ± 7.31 | 20.84 ± 7.63 | 0.87 ± 0.09 |
| Entrained Ergometer Cycling | 24.88 ± 7.10 | 27.31 ± 6.64 | 21.50 ± 6.80 | 0.93 ± 0.05 |
| Unentrained Treadmill Walking | 22.33 ± 8.0 | 22.61 ± 7.36 | 18.27 ± 7.18 | 0.91 ± 0.07 |
| Unentrained Ergometer Cycling | 23.90 ± 6.16 | 24.41 ± 7.22 | 18.93 ± 6.23 | 0.91 ± 0.08 |
| Control Treadmill Walking | 21.29 ± 6.69 | 21.91 ± 8.50 | 16.86 ± 6.86 | 0.88 ± 0.10 |
| Control Ergometer Cycling | 23.74 ± 6.60 | 24.75 ± 7.17 | 18.81 ± 7.47 | 0.92 ± 0.41 |

**Table 4.5** Average Free Recall Memory Data (mean ± SD)

A 2(mode)X3(condition) within-between repeated measures ANOVA of A' recognition memory accuracy found no main effects of mode (F (1,70) = 2.95, p = 0.09, $\eta_p^2 = 0.04$) or condition (F (2,140) = 0.01, p = 0.99, $\eta_p^2 = 0.02$). However, a one-way ANOVA comparison of modality within each condition identified a significant difference when the entrained condition results were compared according to physical activity modality (F(1,70) = 8.82, p = 0.004, $\eta_p^2 = 0.11$) in which the cycling group outperformed the walking group (mean difference p = 0.044).

No similar effects were found for either the unentrained (F(1,70) = 0.02, p = 0.88, $\eta_p^2$ = 0.000) or control conditions (F(1,70) = 1.75, p = 0.19, $\eta_p^2$ = 0.02). The same analytic approach of recognition memory confidence violated sphericity (p=0.04) but still found no main effects of mode (F (1,70) = 0.91, p = 0.34, $\eta_p^2$ = 0.01) or condition (F (1.84,128.58) = 1.38, p = 0.26, $\eta_p^2$ = 0.02) or condition*mode (F (1.83, 128.58) = 3.09, p = 0.053, $\eta_p^2$ = 0.04) using Greenhouse-Geisser corrections. Simple comparisons also found no conditional differences in modality confidence (entrained: p = 0.07; unentrained: p = 0.70; control: p = 0.72). A 3(condition)X3(variable)X(mode) repeated measures MANOVA of DCAT performance also found no effect for condition (F(2, 69) = 0.34, p = 0.72, $\eta_p^2$= 0.01) or mode (F(2,70)= 0.10, p = 0.74, $\eta_p^2$= 0.01).

| | Total Performance (mean ± standard error) | Odds Ratio (mean ± standard error) | Reduction Ratio (mean ± standard error) |
|---|---|---|---|
| Entrained Treadmill Walking | 927.1 ± 37.61 | 1.4 ± 0.23 | 1.39 ± 0.04 |
| Unentrained Treadmill Walking | 895.34 ± 32.09 | 1.23 ± 0.18 | 1.39 ± 0.03 |
| Control Treadmill Walking | 900.44 ± 33.17 | 1.12 ± 0.19 | 1.33 ± 0.04 |
| Entrained Ergometer Cycling | 912.9 ± 29.12 | 1.16 ± 0.14 | 1.53 ± 0.16 |
| Unentrained Ergometer Cycling | 916.94 ± 33.91 | 1.15 ± 0.15 | 1.69 ± 0.37 |
| Control Ergometer Cycling | 933.6 ± 29.41 | 1.07 ± 0.18 | 1.44 ± 0.07 |

**Table 4.6** Digit Cancellation Task Attention Test Results

*Physiological Outcomes Modality Comparison*

When comparing heart rate and RPE data between Experiment 1 and 2, the cycling condition consistently had a slight but significantly higher value. All analyses were run using repeated measures within-between ANOVAs. A heart rate analysis of the 3-minute warm-up showed a main effect of mode (F(2,70) = 32.08, p < 0.001, $\eta_p^2$ = 0.31) but no main effect of condition (sphericity violation p = 0.04, Greenhouse-Geisser correction F(1.83,128.65) = 1.81, p

= 0.17, $\eta_p^2 = 0.02$) or condition*mode interaction (sphericity violation p = 0.04, Greenhouse-Geisser correction F(1.83,128.65) = 0.64, p = 0.53, $\eta_p^2 = 0.009$). The cycling condition had a higher average warm-up heart rate with an overall mean difference of 11.59 bpm. Similar results were found for warm-up RPE with a main mode effect (F(2,70) = 16.5; $p < 0.001$, $\eta_p^2 = 0.19$) with an average mean difference of 0.79 but no effect of condition (F(2,140) = 1.86; p = 0.16, $\eta_p^2 = 0.03$) or condition*time interaction (F(2,140) = 0.01; p = 0.98, $\eta_p^2 = 0.000$).

A third analysis compared heart rate data from both interventions. There was no effect of time (block; F(1,70) = 0.30, p =0.59, $\eta_p^2 = 0.004$). However, there was a significant effect of condition (F(2,70) = 30.6, $p < 0.001$, $\eta_p^2 = 0.30$), mode (F(1,70) = 34.23, $p < 0.001$ , $\eta_p^2 = 0.33$), and a mode*condition interaction (F(2,140) = 4.23, p =.0.021 , $\eta_p^2 = 0.06$). Simple pairwise comparisons revealed significant differences between the walking and cycling intervention's heart rates in the entrained ($p < 0.001$), unentrained ($p < 0.001$), and control conditions (p = 0.005). See Table 4.7 for more information.

### Experiment 2: Brief Discussion

Experiment 2's visual long-term memory results affirm Hypothesis 3's predictions of enhanced long-term memory retention and previous evaluating memory functioning following an entrained CMDT (Schmidt-Kassow et al., 2013a; Schmidt-Kassow et al., 2014). However, Hypothesis 4's prediction in relation to cycling CoV was not supported due to the absence of significant differences in motor production across CMDT conditions. Because of the similarities in the methodological design and psychological assessments used, a comparison of the results from Experiments 1 and 2 is warranted and discussed in detail in the following section.

| | Physical Activity Intensity | Warm-up Heart Rate (mean ± standard error) | Mean difference ± standard error | Warm-up RPE (mean ± standard error) | Mean difference ± standard error | Intervention Heart Rate (mean ± standard error) | Mean difference ± standard error |
|---|---|---|---|---|---|---|---|
| *Entrained Treadmill Walking* | light | 91.94 ± 2.17 | P < 0.001*, 9.94 ± 2.55 | 7.94 ± 0.14 | P = 0.006*, 0.81 ± 0.28 | 91.65 ± 2.27 | P < 0.001*, 16.1 ± 3.25 |
| *Entrained Ergometer Cycling* | light | 101.89 ± 1.83 | | 8.75 ± 0.24 | | 107.70 ± 2.23 | |
| *Unentrained Treadmill Walking* | light | 93.72 ± 1.78 | P < 0.001*, 11.41 ± 2.57 | 7.92 ± 0.11 | P < 0.001*, 0.77 ± 30.23 | 91.34 ± 2.10 | P < 0.001*, 18.1 ± 3.56 |
| *Unentrained Ergometer Cycling* | light | 105.14 ± 1.87 | | 8.68 ± 0.19 | | 109.45 ± 2.49 | |
| *Control Treadmill Walking* | light | 90.17 ± 1.74 | P < 0.001*, 13.41 ± 2.81 | 7.72 ± 0.14 | P < 0.001*, 0.81 ± 0.21 | 84.09 ± 2.16 | P < 0.005* 8.62 ± 3.15 |
| *Control Ergometer Cycling* | light | 103.58 ± 2.06 | | 8.52 ± 0.17 | | 92.71 ± 2.07 | |

**Table 4.7** Experiment 1 & 2 Heart Rate Data Comparison

In the far-right column, an asterisk (*) indicates a significant difference in heart rate during the intervention when the physical activity modes were compared across experiments. Warm-up heart rate and RPE were both significantly different between experiments. Experiment 2's cycling intervention heart rates were, on average, 10-15 bpm higher than Experiment 1'a treadmill walking heart rates.

## Discussion

The present experiments, with their focus on the influence of the cyclical alignment of cognitive stimulation with motor production, offer intriguing insights into long-term free recall and recognition memory retention and the coefficient of variation of motor production. The experiments were designed to explore the potential of creating an environment conducive to neural entrainment during a CMDT to alleviate dual-task costs associated with competition for cortical resources. The findings of this study, building on prior research, could open up new avenues for understanding and improving long-term memory retention (Schmidt-Kassow et al., 2013a) and decreased variation across a variety of gait cycle parameters (Braun Janzen et al., 2022; Scott et al., 2025; Thaut et al., 2015). Long-term memory findings relating to predictions from Hypothesis 1 and 3 parallel to those found in prior published experiments. However, no long-term memory differences were found concerning Hypothesis 5's predictions regarding physical activity modality, and no CoV differences were identified in relation to the consistency of motor performance (Hypothesis 2 and 4) during treadmill walking or ergometer cycling. While cognitive-motor dual tasks traditionally lead to impaired performance due to limited cognitive resources forcing task prioritization (Yogev-Seligmann et al., 2012), the beneficial cognitive effects and the absence of any motor DTC in Experiments 1 and 2 suggest that creating entrainment-supporting environments during a CMDT may not only alleviate detriments commonly seen during concurrent task production but also have practical implications for improving cognitive-motor performance in real-world scenarios.

### *Long-Term Free Recall Memory*

In both Experiment 1 and Experiment 2, participants performed significantly better on long-term memory retention tests when words were encoded under the entrained condition. In Experiment 1, free-recall long-term memory assessments following the entrained condition led to significantly more words recalled than memory assessments following the control condition ($p = 0.03$). Similarly, in Experiment 2, free-recall long-term memory assessments following the entrained condition led to significantly better free-recall long-term memory performance when compared to words learned under both the unentrained and control conditions (p = 0.03). In both cases, the conditional effect was found regardless of the time of long-term memory assessment (immediate, 10-minute, or 24-hour) with the medium partial eta square effect size of 0.1. These results align with the medium-large positive effect sizes found in similar studies reporting long-term memory outcomes (Schmidt-Kassow et al., 2013a; Scott, 2023). Taken together, the consistency in findings from published experiments in which stimuli presentation is cyclically aligned to motor production implies that this approach may overcome the DTCs of poor network efficiency and functional connectivity commonly associated with traditional CMDTs (Ding et al., 2024).

The Theory of Dynamic Information Selection by Entrainment (DISE) can be used to explain the mechanisms behind these outcomes based on assumed changes in an individual's neural activity relating to their body, perception, and the environment (Lakatos et al., 2019). According to DISE, entrained neural oscillations create an environment in which afferent signals of external stimulation align with cortical information processing systems. The entrained patterns of high and low neural excitation are thought to enhance attentional capacity and decrease cognitive load, ultimately benefitting cognitive functioning overall (Calderone et al., 2014; Lakatos et al., 2008). Based on recent discoveries concerning cortical input, neurophysiologists support DISE by proposing that the brain naturally processes exteroceptive information through the spontaneous convergence of intrinsic neural timescales, interoceptive signaling, and incoming neural activity patterns (Charalambous & Djebbara, 2023; Golesorkhi et al., 2021). The methodological design of the present experiments likely facilitated the occurrence of these entrainment effects, leading to the measured enhancements in long-term free recall memory.

### *Long-Term Recognition Memory*

While the entrained condition in both the ergometer cycling and treadmill walking experiments enhanced long-term memory functioning, no effect was seen in recognition memory accuracy A' outcomes for Experiment 1 or 2. Scott et al. (2025), the only other study of this kind that methodologically sought to indue entrainment through a CMDT, also found results in which mnemonic benefits were seen in free-recall but not recognition long-term memory tests. Although the word lists presented in Scott et al.’s (2025) experiment were presented auditorially instead of visually, as in the present experiments, these patterns of outcomes suggest that CMDT interventions may be more likely to benefit particular memory assessments over others.

Free recall and recognition memory retrieval are thought to rely on different neurological pathways for information retrieval. In the seminal Search of Associative Memory (SAM) model of memory processing, Atkinson and Shiffrin (1968) consider episodic memory retrieval to be founded in a search of memory traces with varying engram strengths. Free recall memory, or remembrance, is determined based on a match between a stimuli or context cue and one memory trace. In contrast, recognition memory is representative of familiarity with the stimuli and the cumulative activation of all memory traces (Malmberg et al., 2019). The type of CMDT entrainment methodologically induced in the present experiment may only provide mnemonic benefits to one of these retrieval pathways. However, due to neurophysiology's rudimentary understanding of memory's underpinnings, much more research is needed before conclusions about these factors can be made (Frankland et al., 2019).

Participants' expectations of consecutive long-term memory testing may have also influenced the results. In a foundational experiment on memory, Hall et al. (1976) discuss how informing individuals of the type of memory assessment they would receive influenced retention outcomes, with those expecting free recall assessments performing better than those who knew a memory test would follow. Participants in this experiment were instructed to say as many words as they could remember aloud following each encoding trial. While they were not explicitly told that the long-term memory retention test would replicate this format, their prior experience with this approach may have caused them to expect this task in the future. Recognition memory tests, administered without warning as the last assessment in the 24-hour session, may have surprised some participants, leading to decreased task performance during session three. The other sessions in which 24-hour recognition memory assessments were administered occurred during sessions five and seven. Due to the parallel procedures used throughout both experiments, participants were likely able to anticipate the presentation of a recognition memory assessment, decreasing the likelihood of test expectancy influencing differences found between free-recall and recognition memory outcomes.

In addition to the A' accuracy measurements discussed above, a secondary analysis from Experiment 2 found a significant difference in recognition memory confidence. Participants felt more confident in their answers following the cycling entrained condition compared to the unentrained or control conditions. Confidence and accuracy in recognition memory are highly related, and asking participants to report their confidence in a memory assessment response provides insight into the participant's psychological state during long-term memory tests (Mickes, 2015; Roediger III & Tekin, 2020; Yonelinas, 2001). It is possible that participants were more at ease during the entrained condition in Experiment 2, leading to increased confidence during follow-up assessments. As this is the first study of its kind to collect recognition memory confidence levels, more research is needed to conclude the meaning of the conditional changes in recognition memory. Future entrained CMDT research should continue collecting confidence data to clarify what types of further insight this added component could provide.

### *Memory and Physical Activity Modality*

Contradicting the proposed expectations from Hypothesis 5, physical activity modality differences between Experiment 1 and 2 did not statistically influence long-term memory hypotheses. However, mean ergometer cycling free-recall scores in Experiment 2 were consistently about one word higher than those from Experiment 1. Due to the high levels of variation within the sample, the series of experiments may have needed more power to identify statistical differences between the two groups. Across the warm-up and intervention, heart rate and RPE in Experiment 1 were slightly lower than in Experiment 2. While the significant differences in physical activity intensity may have influenced outcomes, all average heart rates and RPEs fall into the "very light" classification of physical activity intensity (Liguori & Medicine, 2020). In prior experiments with very similar methodological designs (Schmidt-Kassow et al., 2013d), cycling and walking heart rates and RPEs fall within the same "very light" intensity range. Because physical activity intensity in the two present experiments match each other and prior experiments, it is unlikely this factor prevented the identification of long-term memory retention differences in regards to physical activity modality.

Researchers hypothesize that motor task complexity, specifically the degrees of freedom included in a CMDT, could alter long-term memory retention (Schmid, 2024; Schmidt-Kassow & Kaiser, 2023; Tomporowski & Qazi, 2020). Ergometer cycling requires fewer degrees of freedom for motor task production than walking (Raasch & Zajac, 1999). For example, balance and arm-leg movement coordination are important factors while walking but much less relevant during ergometer cycling CMDT. Therefore, performance in Experiment 2 was expected to be better than that of Experiment 1 due to differences in physical activity complexity and available neural resources. However, these differences may have been so slight that the resultant influence on cognitive function was negligible. A post-hoc sensitivity analysis was conducted to determine what effect might be identified given the sample parameters (G*Power: F tests, Repeated measures within-between interaction sensitivity analysis: $\alpha = 0.05$, Power = 0.95, n = 72). The results indicated that a minimum effect of Cohen's D = 0.38/f = 0.19 could be found. Therefore, the sample is significantly underpowered to identify a small underlying effect of modality.

The lack of significant findings may also be due to the similarities in muscle synergies between both physical activity modalities. Cycling and walking share common neuromuscular mechanisms that activate coordinated cascades of neural activation patterns, often referred to as muscle synergies (Barroso et al., 2014). Muscle synergies decrease the computational burden required to execute learned motor actions by executing a motor program using premade coordinated patterns of neural activation (Singh et al., 2018). Perhaps the participants' prior experience in walking and cycling allowed them to use muscle synergies to execute the motor task components in Experiments 1 and 2, decreasing the computational burden required and the likelihood of identifying the hypothesized cognitive performance differences. More research is needed to elucidate these questions and determine if CMDT entrainment may have differential effects on particular physical activity modalities.

### *Motor Task CoV*

In relation to Hypotheses 2 and 4, neither Experiment 1 nor 2's coefficient of variation analyses identified conditional differences during treadmill walking or ergometer cycling. While one prior experiment has indicated that variation in healthy, young-adult motor performance production may decrease during an entrained CMDT (Scott et al., 2025), most of the existing research has been collected in a therapeutic setting (Braun Janzen et al., 2022; Thaut et al., 2015). In comparison to a sample of patients with motor impairments, young adults' standard low levels of variation in ergometer cycling and treadmill walking may have limited the range of the CoV data collected (Schmitt et al., 2021). Additionally, the absence of a statistical difference in cycling and walking CoV between the unentrained CMDT and the single-task baseline suggests that motor DTC was not induced by the methodological design of either study. Perhaps the motor tasks' simplicity, referenced in the modality section above, minimized the potential for the variation seen in CoV. Future studies should increase the complexity of an entrained CMDT to evaluate if increasing the difficulty of motor task performance may reveal CoV benefits from entrainment. For example, participants might be asked to pace themselves on a manual treadmill, complete overground walking, or cycle a bike on rollers. All of these examples increase balance demands and require a higher level of conscious awareness during motor performance, increasing the difficulty of motor task execution and more closely mirroring possible translational applications of laboratory experimental findings.

### *Limitations and Future Research*

While statistical analyses from Experiment 1 and 2 reflect positive cognitive outcomes, there are a number of limitations that limit the generalizability of these findings. Most importantly, although methodological design created an opportunity for neural entrainment to occur, the absence of physiological measurements of neural wavelength activity limits conclusions that can be made regarding the mechanisms behind each finding. Based on evidence from prior studies, alterations in neural activation likely took place (Lakatos et al., 2019), but the available data do not allow for testing this assumption. Ideally, phase response curves reflecting the presentation of EEG data would be used to calculate possible shifts in neural activation pattern frequency and identify the presence of neural entrainment. Without this confirmation of neural activation patterns, it is important to acnowledge that alternative factors may have contributed to the mnemonic benefits identified.

The rhythmic consistency of word presentation during the entrained condition may have allowed participants to predict when stimuli would appear and focus their attention accordingly. For example, Jones and Ward (2019) presented a recognition task in rhythmic patterns, leading to superior recognition memory compared to trials using unpredictable stimuli presentation. EEG data support these conclusions by revealing conditional FN400 ERP activation patterns associated with memory functioning. The authors suggest that the rhythmicity and predictability of stimuli influence neural processing and provide mnemonic effects by allowing the participant to prioritize attentional orientation at particular times throughout encoding. Ideally, a second control condition could have been added to the study in which participants were presented with words at a rate that matched the entrained CMDT condition. However, because this type of control had previously been used in Scott et al.'s (2025) experiment, this condition was excluded from the present study's methodological design to avoid adding extra time to the burden of laboratory testing for participants. Future research should extend this work by incorporating rhythmic stimuli presentation during a single-task control condition and physiological analyses to check the validity of environmentally induced entrainment at the neurological level (Rosso et al., 2021).

Overall, much more research is needed to understand the underlying mechanisms of the observed results in Experiments 1 and 2 and to understand how to translate positive laboratory results to natural environments. Participant characteristics limit the generalizability of the present findings. In both experiments, healthy young adults between 18 and 30 years old comprised the sample. In contrast to older adults or children, healthy young adults have the highest levels of resiliency to a CMDT, resulting in lower DTC measurements (Boisgontier et al., 2013; Doumas et al., 2009; Ruffieux et al., 2015). Older adults and children may experience more significant benefits from CMDT entrainment; however, no studies have evaluated these subsets of the population using methodological approaches similar to the present experiments. If future experiments assess the effects of entrainment on CMDT interventions in children and older adults, the results may help researchers identify how to translate the laboratory findings to real-world settings and optimize the beneficial impacts of this work.

## Conclusion

Across both present experiments, entraining a CMDT dual task leads to enhanced long-term memory performance regardless of the mode of physical activity performed. Free-recall memory assessments revealed long-term memory differences, while no significant differences were found across recognition memory accuracy tests. The variation in motor performance of treadmill walking and ergometer cycling was not statistically different from that of a traditional dual-task and a single-task baseline analysis. Together, these results indicate that the entrainment of a CMDT may help individuals increase memory performance and avoid motor costs associated with dual-tasking.

While the mechanisms behind these outcomes are still unclear, cognitive-motor entrainment likely decreased the cognitive load, increased neural efficiency, and improved attentional allocation required to perform concurrent tasks. Future research should implement similar experimental methodologies while assessing neural activity to provide a physiological explanation for Experiments 1 and 2's findings. Increased sample sizes and the variation of sample characteristics, such as age and health status, may reveal the nuances of entrainment relationships, helping researchers identify the circumstances in which its translational implementation has the highest likelihood for positive outcomes. Additionally, the evaluation of both cognitive and motor performance quality within dual-task experiments is essential to understanding the full impact of CMDT entrainment.

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# CHAPTER 5

# BASELINE LONG-TERM MEMORY AS A MODERATOR OF COGNITIVE-MOTOR ENTRAINMENT[1]

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# Abstract

Cognitive-motor entrainment has been shown to enhance long-term memory retention and protect individuals from dual-task costs commonly associated with concurrent task production. However, little is known about what subset of the population may be most likely to benefit from this type of intervention. To explore this concept, the present study conducted a secondary analysis of data to understand how individual baseline long-term memory capabilities may mediate cognitive-motor entrainment’s mnemonic effects on long-term memory. Long-term memory free recall retention data from Chapter 5’s Experiments 1 and 2 were combined, and participants were sorted into quartiles based on a baseline ModRey free-recall long-term memory analysis. While participants in the lowest quadrant were expected to reap the largest benefits from the cognitive-motor entrainment intervention, no significant differences were found between groups.

# Introduction

Recent experimental evidence reflects a positive association between acute physical activity interventions and cognitive functioning (Chang et al., 2012; Erickson et al., 2019; Griebler et al., 2022; Hillman et al., 2019; Loprinzi et al., 2021a; Schmid et al., 2023). However, as researchers seek to understand the intricacies of this relationship, inconsistencies in the data and the absence of positive findings within particular experiments have become a cause for concern (de Greeff et al., 2018). By considering factors that may lead to variation in outcomes, such as age (Chang et al., 2012; Erickson et al., 2015; Ludyga et al., 2016), sex (Johnson et al., 2019; Johnson & Loprinzi, 2019), the timing of physical activity (Loprinzi et al., 2019a; Loprinzi et al., 2021a), response or sensitivity to physical activity (Herold et al., 2019; Ross et al., 2019; Schwarck et al., 2019), and physical fitness (Chang et al., 2012; Etnier et al., 2006; Gronwald et al., 2020; Li et al., 2019), the characteristics of individuals who have the highest capability to cognitively benefit from acute physical activity interventions may be identified. While understudied, varying levels of baseline cognitive functioning have been shown to contribute to inherent intraindividual differences between participants and interindividual differences between samples that may muddle experimental findings (Ishihara et al., 2020; Ishihara et al., 2021). Due to the practical relevance of understanding how cognitive individual differences influence physical activity’s effects, determining which participant characteristics increase an intervention’s propensity for success may help scientists identify a promising target population for future research (Herold et al., 2021).

Children with lower baseline cognitive ability have been shown to benefit more from acute physical activity interventions through increased on-task behavior (Mahar, 2011) and response accuracy and interference (Drollette et al., 2014) when compared to their peers with average or advanced cognitive functioning. Moreover, adults with lower baseline cognitive abilities experience similar outcomes (Ishihara et al., 2021). Recently, an individual participant data meta-analysis was conducted, including 2,796 cases, with the goal of understanding how inconsistencies in experimental design influenced outcomes related to acute physical activity's effect on cognition. The authors hypothesized that pre-test baseline cognitive performance would moderate acute aerobic exercise's effect on executive functioning. Results supported the hypothesis, reflecting consistent cognitive benefits for those with low baseline ability across a variety of executive functioning categories. Due to the use of the current gold-standard technique for meta-analyses (Riley et al., 2010), these findings are compelling as they provide insight for future research by indicating which subset of the population should be included in an experiment to magnify an intervention's positive effects.

Individual differences in physical activity’s effects on cognition have also been identified experimentally. In a study evaluating exercise’s impact on cognition, Sibley and Beilock (2007) asked healthy young adults to walk on a treadmill for 30 minutes at moderate intensity as they completed the Operation Span and Reading Span working memory tests. When walking, dual-task working memory performance was compared to a seated baseline assessment. Outcomes differed based on the participant’s foundational working memory capabilities. Participants with the lowest quartile working memory scores benefitted from the exercise intervention, while those in the upper three quartiles did not. Yamazaki et al. (2018) report very similar results in which baseline working memory capabilities were associated with cognitive processing speed regardless of the intensity of aerobic exercise on a cycle ergometer. Those with low foundational working memory capacity experienced larger cognitive benefits following the physical activity intervention. The reported variations may be related to an individual's capacity for relative change in cortical activation patterns.

Furthermore, a secondary analysis of data from two experiments in children (Hillman et al., 2009; Pontifex et al., 2013) found that baseline task performance differentially impacted acute physical activity's effect on cognition and was associated with cortical activation magnitude at N2 and P3 event-related potentials (Drollette et al., 2014). Single-task inhibitory capabilities were measured using the modified flanker task and used to categorize participants into a "low-performance" and "high-performance group." Those in the low-performance group had higher response accuracy and decreased interference levels following a 20-minute bout of moderate-intensity treadmill walking. In contrast, the high-performance group did not experience these cognitive benefits at the same magnitude. The researchers also identified alterations in cortical activation patterns associated with these results. Both groups experienced smaller N2 amplitudes and shorter P3 latencies following exercise, but lower performers alone experienced an increase in P-3 amplitude as well. Although this is the only experiment of its kind to measure how individual differences in cortical activation patterns following exercise might influence cognitive processing, the results affirm that exercise's positive cognitive effects may be more pronounced in those with lower foundational executive functioning abilities.

While most individual difference evaluations focus on executive functioning, data from a physio-neuroendocrinological experiment brings forward the idea that individuals with lower cognitive long-term memory abilities at baseline will benefit more from a cognitive-motor dual-task intervention (Schmidt-Kassow et al., 2013d). In this experiment, participants learned 80 Polish-German word pairs and were randomly assigned to one of three learning conditions: cycling before learning, cycling during learning, or seated rest before learning. While participants in both physical activity groups remembered more words at a 48-hour follow-up test, individuals with lower verbal long-term memory capacity performed significantly better only in the condition in which the motor and cognitive task was performed concurrently. Because the concurrent condition presented auditory stimuli synchronously with continuous motor activation patterns, the methodological design was thought to induce cognitive-motor entrainment. Cognitive-motor entrainment has been shown to facilitate the circumvention of dual-task costs and produce mnemonic long-term memory benefits, as seen in Chapter 4 and previous experiments (Rössler et al., 2024; Schmidt-Kassow et al., 2019; Schmidt-Kassow et al., 2014; Scott, 2023), understanding how foundational individual differences moderate this relationship may clarify how this type of dual-task may be used to support individuals with different cognitive capabilities and facilitate the translation of laboratory findings to organic, real-world settings.

As the methodological design from the two experiments in Chapter 4 systematically replicates that of Schmidt-Kassow et al. (2013d), the data warrants an individual differences analysis to determine if baseline long-term memory abilities moderate the impact of the dual-task physical activity intervention on cognitive outcomes. In both experiments, participants were asked to remember 40-word lists under one of three learning environments: an entrained cognitive-motor dual-task condition, an unentrained cognitive-motor dual-task condition, and a sedentary, single-task condition. Outcomes indicated that the entrained cognitive-motor dual-task condition resulted in the highest memory retention. Taking these findings and prior results from individual differences analyses into account, participants with lower levels of baseline long-term episodic memory ability were hypothesized to have experienced larger mnemonic benefits from the entrained condition than individuals with high baseline long-term memory functioning.

# Methods

This study combines data from two prior experiments that evaluated the impact of cognitive-motor entrainment on long-term memory retention. Due to the large sample sizes commonly needed to identify moderating relationships, individual participant data from both within-subject crossover experiments were compiled into one unified data set to increase the sample's power (Brookes et al., 2004). The total number of participants was 72. All the experimental procedures used to collect data were preapproved by The University of Georgia's Institutional Review Board and listed in an informed consent waiver signed by each participant prior to their enrollment in the experiments.

## *Participants and Recruitment*

Inclusion Criteria: Participants included 18 to 30-year-old young adults who spoke English as their first language. Individuals were ineligible to participate if they (a) were diagnosed with cardiovascular, neuromuscular, musculoskeletal, or rheumatoid disorders; (b) used a major psychoactive medication within the past 12 months (e.g., antidepressants); (c) had a movement disorder or an injury or surgery affecting movement within the past 12 months; (d) were diagnosed with a memory or learning disorder (e.g., ADHD, dyslexia) or balance disorders (e.g., vertigo); (e) were pregnant; or (f) had previously participated in a dual-task research project measuring memory.

Because no individual moderating differences were found according to participant sex in similar experiments (Johnson & Loprinzi, 2019; Schmidt-Kassow et al., 2014), both men and women comprised the sample. Participants were recruited using flyers, emails, university classroom presentations, and word of mouth. To express interest in the study, participants completed a Qualtrics survey and were compensated $60 in cash for study completion (or at a rate of $10/hour). Participation took about five and a half hours across seven sessions.

*Surveys and Questionnaires*

A *self-administered medical history questionnaire* and *Godin leisure time physical activity questionnaire* collected demographic information during experimental enrollment (Godin & Shephard, 1985), and a *24-hour health history questionnaire* was completed at every session to track sleep, caffeine intake, drug and alcohol consumption, and exercise.

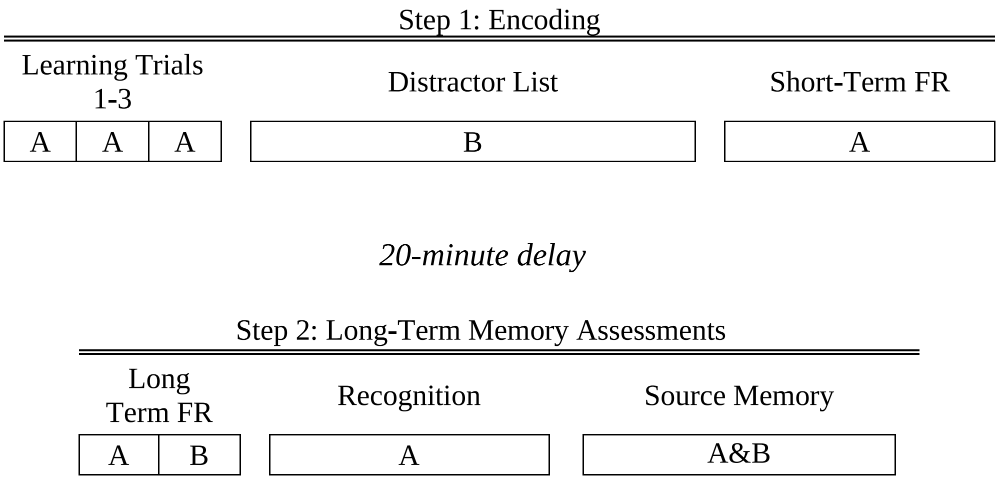


**Figure 5.1** ModRey Assessment Procedures (Hale et al., 2019)

*ModRey Baseline Long-Term Memory Assessment*

To maximize the translational relevance and statistical merit of a study, Moreau et al. (2016) argue researchers should consider how categorical psychological variables will be split before initiating an individual differences analysis. Best practice recommends that researchers use a psychometric test with normative data that is reflective of the population from which a sample was selected. However, because most long-term memory analyses are developed for older adults or individuals with memory impairments, the majority of established psychometric tests do not sensitively measure memory in a healthy, young adult population (Hale et al., 2019). Because of this, the present experiment used a modified version of the RAVLT called the Modified Rey Auditory Verbal Learning Test, or the ModRey for short (Hale et al., 2019). While limiting the generalizability of the findings, this approach decreases the likelihood of ceiling effects in baseline long-term memory data to more accurately measure individual differences in cognitive ability.

The ModRey's methodology closely follows the Rey Auditory Verbal Learning Test (RAVLT) by presenting auditory verbal stimuli in the form of word lists during an encoding period. However, ModRey participants complete only three encoding trials of 20 unrelated words that comprise List A instead of the RAVLT's five encoding trials of 15 words. Following each of the ModRey's encoding trials for List A, participants are asked to repeat as many words as they can remember from the list aloud. Next, they hear List B, which includes 20 new words, and repeat back as many words as they can remember from this distractor list. They complete the learning assessment by free-recalling List A without hearing the stimuli list. After a time delay, participants are tested on long-term free recall of List A words and List B words. This is followed by a List A recognition test that asks participants to identify List A stimuli amidst novel and distractor words from List B. Finally, they complete a source memory trial in which participants distinguish from which list each word came. In the included experiments, the time delay between the end of the learning trial and the long-term memory assessment was about 20 minutes. To ensure that a baseline long-term memory score from the ModRey was similar to the primary long-term memory assessments included in the experiments, only the final long-term free-recall memory assessment from List A was used as a baseline reference of cognitive ability.

### *Word Lists and Memory Tests*

Participants studied three unique lists of 40 words from a similar experiment evaluating the relationship between long-term memory and physical activity (Loprinzi et al., 2023; Wilson, 1988). Words were visually presented for 500 ms using the Superlab Psychological software (SuperLab 6, Cedrus) and Stimtracker hardware (Stimtracker Duo, Cedrus) at a preprogrammed pace and separated by a fixation cross. Participants studied the same list in the same order twice during each learning condition. They learned the word lists under three distinct presentation conditions. In an "entrained" dual-task condition, participants viewed words presented consistently that aligned with their motor production pattern. In the unentrained dual-task condition, words were presented randomly as participants performed a motor task. Unlike the entrained condition, the delay between each word presentation in the unentrained condition varied. Finally, in a single-task condition, participants were stationary as they viewed words with the exact timing as the unentrained condition. The total study time for each word list was the same across all three conditions.

Free recall and recognition memory tests assessed long-term memory performance. In free recall assessments, participants are unprompted as they state as many words as they can remember from the list aloud. During recognition memory assessments, participants were asked to indicate "yes" they had or "no" they did not recognize a word displayed in a slideshow and indicate their confidence in this answer as "high," "moderate," or "low" (Yonelinas et al., 1996). The value A' was calculated to analyze the relation between hits and false alarms via the following formula $A' = \frac{1}{2} + (\frac{(y-x)(1+y-x)}{4y(1-x)})$ where $x = \frac{false\ alarms}{distractor\ words}$ and $y = \frac{hits}{List\ A\ words}$ (Yonelinas & Parks, 2007).

### *Statistical Analysis*

When considering the appropriate statistical analysis to use to evaluate data in the present study, the division within the present literature indicates a lack of consensus regarding the classification of a moderating and interaction effect in a repeated measures analysis (Judd et al., 2001; Montoya, 2019; VanderWeele, 2009). Because a moderator's effect can be statistically categorized as an interaction and repeated measures within the subject design do not permit a traditional moderation analysis (Robinson et al., 2013), baseline long-term memory was added as an interaction term to the original time by condition repeated measures model.

## Procedures

All seven testing sessions started with a 24-hour history questionnaire and were scheduled at the same time of day (+/- 1 hour) to decrease external error. In session 1, participants first signed consent forms and completed questionnaires (self-administered medical history, 24-hour health history, and Godin leisure-time exercise. Researchers then evaluated demographic characteristics (resting heart rate, height, and weight) before guiding participants through the learning portion of the ModRey baseline long-term memory assessment (Hale et al., 2019) and baseline motor assessment to determine the intensity of physical activity that would be used in the rest of the experiments. At the end of the session, the long-term memory assessments from the ModRey test were administered.

The following sessions, two and three, four and five, and six and seven, were differentiated based on the assigned world-learning condition: entrained, unentrained, and control. On even numbered session days, participants studied a word list under three possible experimental conditions. In the entrained condition, motor performance was entrained to cognitive stimuli presentation. In the unentrained condition, words were presented randomly as participants completed a motor task. In the control condition, participants were stationary as words were displayed following the unentrained condition's presentation pattern. The study time across all learning conditions was relatively equivalent. After the word learning task, the participant completed a 3-minute Digit Cancellation Task (DCAT) to prevent rehearsal before a long-term memory free-recall assessment (Hatta et al., 2012). They then sat quietly for 10 minutes before a final free-recall memory assessment. Odd-numbered session days were used as a 24-hour follow-up to assess long-term memory retention. Participants completed a free recall test followed by a recognition test. The seventh session also included a debrief explanation in which research assistants answered any questions participants had about the study’s design and were compensated for the completion of the experiment. Sessions three and four, as well as five and six, were separated by 24 or 48 hours.

## Results

### *Participants and Enrollment*

Two hundred seventy people expressed interest in the study through a Qualtrics survey. These individuals were contacted by email to confirm compliance with inclusion and exclusion criteria. Ultimately, 77 participants enrolled in the two experiments, with five being excluded for procedural non-compliance or errors during data collection, leaving data from 72 participants included in the present analyses.

| Quartile | Number of Participants | List A Words Free-Recalled |
|---|---|---|
| **Low** | 1 | 2 |
| | 1 | 3 |
| | 3 | 4 |
| | 4 | 6 |
| | 9 | 7 |
| **Low-Moderate** | 9 | 8 |
| | 9 | 9 |
| **Moderate-High** | 9 | 10 |
| | 5 | 11 |
| | 4 | 12 |
| **High** | 7 | 13 |
| | 2 | 14 |
| | 6 | 15 |
| | 1 | 16 |
| | 1 | 17 |
| | 1 | 18 |

**Table 5.1** Baseline Long-Term Memory Distribution and Quartiles

*Data preparation*

A median absolute deviation method was used to clean data prior to statistical analysis. Raw baseline long-term memory data was used to classify participants into quartiles based on the final analysis of List A free-recall word retention. This technique follows recommendations from Moreau et al. (2016) and precedent from prior studies that grouped participants into cognitive ability categories to evaluate the effects of physical activity on cognition (Drollette et al., 2014;

Schmidt-Kassow et al., 2013d; Sibley & Beilock, 2007; Yamazaki et al., 2018). See Table 5.1 for the general distribution of baseline long-term memory scores across participants.

### *Long-Term Memory Statistical Model*

Long-term free-recall memory results were analyzed using a within-between 3(time)X3(condition)X4(quartile) repeated measures ANOVA. Box's test of equality of covariance matrices was nonsignificant (p = 0.147), indicating that the observed covariance matrices across data points are equal. Mauchly's test of sphericity was violated for condition (p = 0.05) and time (p = 0.03); therefore, Greenhouse-Geisser corrections were used when reporting the following within-subject effects.

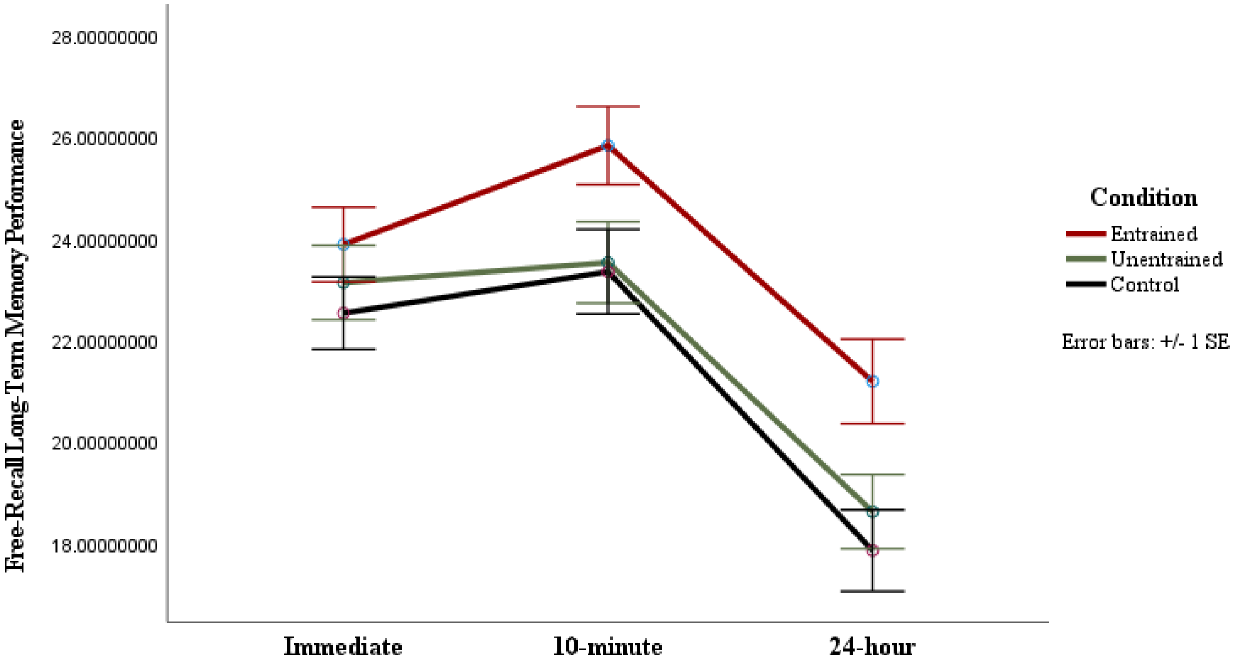


**Figure 5.2** Free-Recall Long-Term Memory Performance Across Time by Condition

| Time | Quartile | low | low-moderate | moderate-high | high |
|---|---|---|---|---|---|
| Immediate | low | | | | |
| | low-moderate | p = 0.03* | | | |
| | moderate-high | P < 0.001* | p = 0.04* | | |
| | high | P < 0.001* | P < 0.001* | p = 0.14 | |
| 10-minute | low | | | | |
| | low-moderate | p = 0.08 | | | |
| | moderate-high | P < 0.001* | p = 0.06 | | |
| | high | P < 0.001* | P < 0.002* | p = 0.21 | |
| 24-hour | low | | | | |
| | low-moderate | p = 0.04* | | | |
| | moderate-high | P = 0.003* | p = 0.28 | | |
| | high | P < 0.001* | P < 0.04* | p = 0.34 | |

**Table 5.2** Simple Pairwise Comparisons from the Quartile*Time Interaction Effect

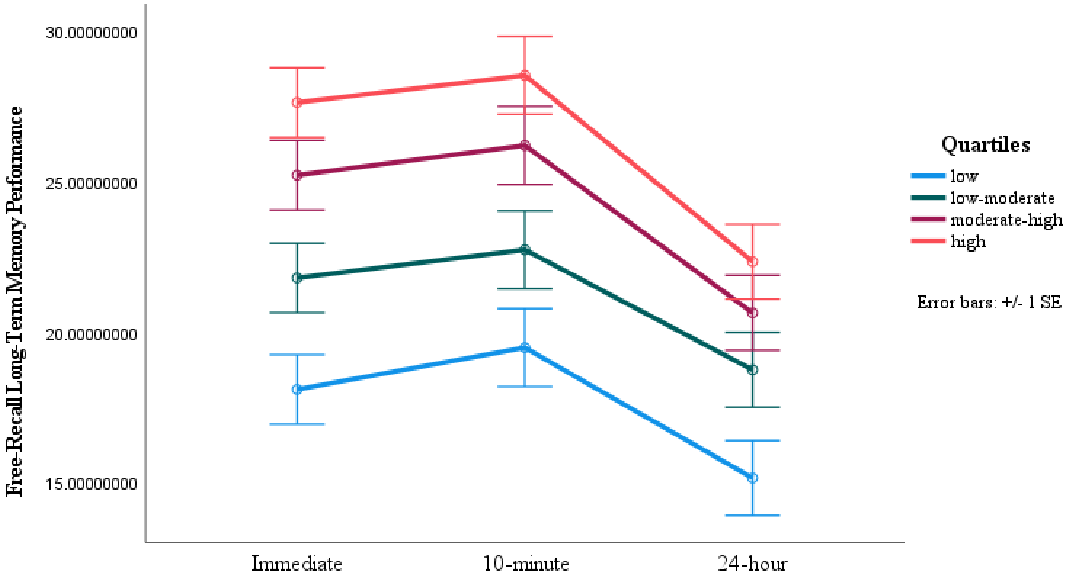
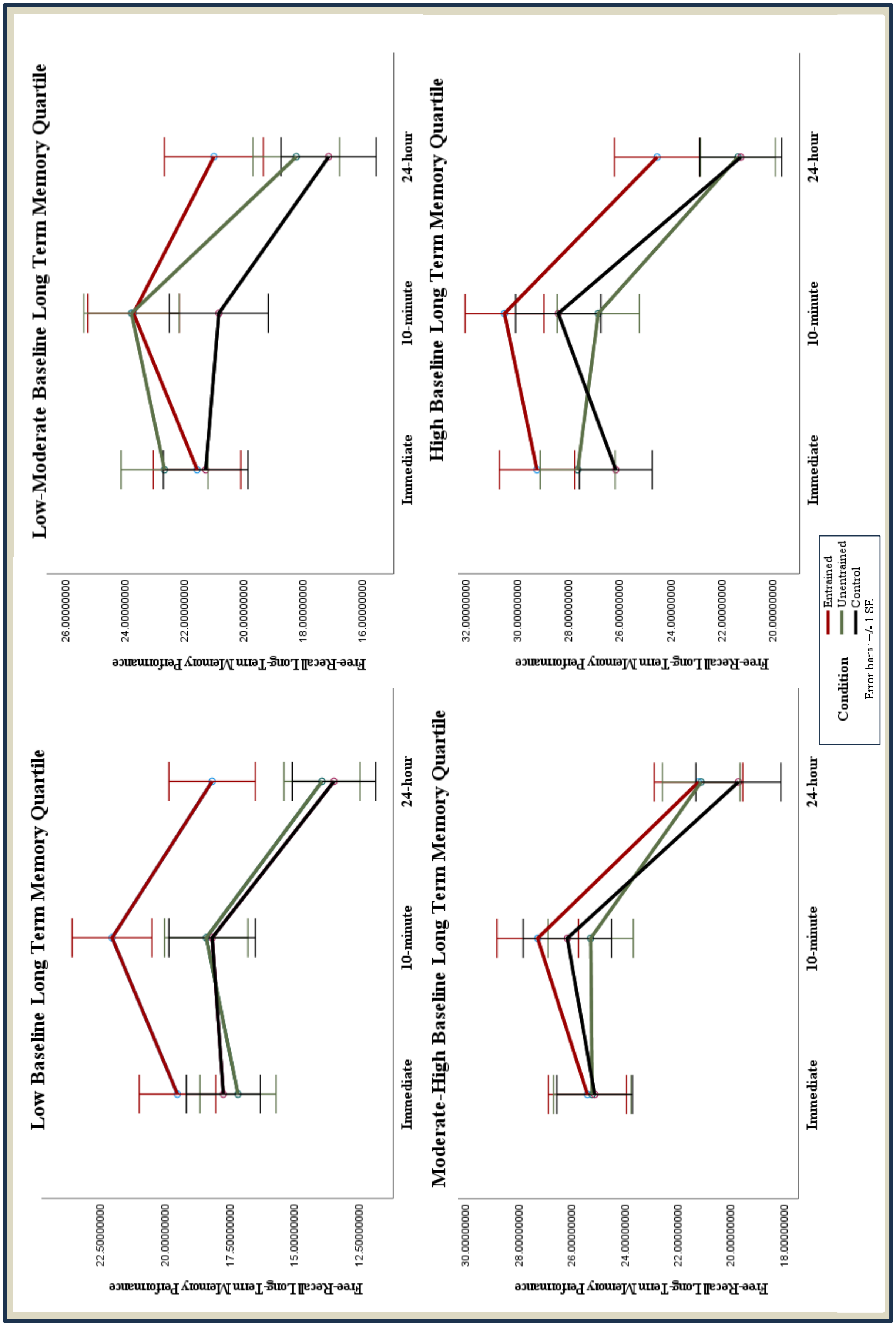


**Figure 5.3** Free-Recall Long-Term Memory Performance Across Time by Quartile (above)

**Figure 5.4** Each Quartile’s Long-Term Free-Recall Memory Performance By Condition (below)


Low Baseline Long Term Memory Quartile
Free-Recall Long-Term Memory Performance
22.50000000
20.00000000
17.50000000
15.00000000
12.50000000
Immediate
10-minute
24-hour
Low-Moderate Baseline Long Term Memory Quartile
Free-Recall Long-Term Memory Performance
26.00000000
24.00000000
22.00000000
20.00000000
18.00000000
16.00000000
Immediate
10-minute
24-hour
Moderate-High Baseline Long Term Memory Quartile
Free-Recall Long-Term Memory Performance
30.00000000
28.00000000
26.00000000
24.00000000
22.00000000
20.00000000
18.00000000
Immediate
10-minute
24-hour
High Baseline Long Term Memory Quartile
Free-Recall Long-Term Memory Performance
32.00000000
30.00000000
28.00000000
26.00000000
24.00000000
22.00000000
20.00000000
Immediate
10-minute
24-hour
Condition
Entrained
Unentrained
Control
Error bars: +/- 1 SE

The model resulted in a significant main effect of time (F(1.82, 123.51)= 171.10, $p < 0.001$, $\eta_p^2 = 0.72$) and condition (F(1.84, 125.13)= 7.03, p = 0.001, $\eta_p^2 = 0.09$). See Figure 5.2 for a graphical representation of this data. No time*condition interaction (F(3.69, 250.79) = 2.17, p = 0.07, $\eta_p^2 = 0.03$), condition*quartile interaction (F(5.52, 125.13) = 0.71, p = 0.63, $\eta_p^2 = 0.03$) or condition*time*quartile interaction (F(11.06, 25.79) = 0.94, p = 0.54, $\eta_p^2 = 0.04$) were identified. A quartile*time interaction (F(5.45, 123.51) = 2.49, p = 0.03, $\eta_p^2 = 0.10$) was found and further differentiated using simple pairwise comparisons outlined below in Table 5.2 and Figure 5.3.

| | | Immediate to 10-minute Difference Score | 10-minute to 24-hour Difference Score |
|---|---|---|---|
| Quartile 1 (low) | *Entrained* | 2.51 ± 2.91 | -3.85 ± 4.50 |
| | *Unentrained* | 1.22 ± 3.69 | -4.46 ± 4.30 |
| | *Control* | 0.43 ± 3.77 | -4.69 ± 4.01 |
| Quartile 2 (low-moderate) | *Entrained* | 2.14 ± 4.18 | -2.71 ± 3.79 |
| | *Unentrained* | 1.11 ± 2.84 | -5.55 ± 3.62 |
| | *Control* | -0.44 ± 2.77 | -3.70 ± 5.75 |
| Quartile 3 (moderate-high) | *Entrained* | 1.87 ± 3.91 | -6.06 ± 4.75 |
| | *Unentrained* | 0.05 ± 5.11 | -4.17 ± 4.91 |
| | *Control* | 1.03 ± 2.35 | -6.45 ± 4.67 |
| Quartile 4 (high) | *Entrained* | 1.26 ± 4.08 | -5.97 ± 5.29 |
| | *Unentrained* | -0.80 ± 4.17 | -5.46 ± 3.17 |
| | *Control* | 2.24 ± 5.59 | -7.13 ± 4.96 |

**Table 5.3** Long-Term Memory Difference Scores by Quartile

## Discussion

The present secondary analysis of data from two experimental studies evaluated the moderating influence of baseline long-term memory retention abilities on the relationship between physical activity and cognitive functioning. In each experiment, participants completed a cognitive-motor dual-task in which cognitive stimuli presentation was entrained to the participant’s motor patterns, a traditional cognitive-motor dual-task in which stimuli were presented randomly, and a sedentary cognitive task. The original analysis of the data supported the hypothesis that entraining cognitive and motor tasks enhances long-term episodic memory retention and decreases dual-task costs associated with the concurrent production of a motor and cognitive task. To evaluate if individual differences may have influenced these effects, the moderating analysis used baseline long-term memory scores, collected using the ModRey assessment during study enrollment, to classify participants into one of four memory performance quartiles: low, low-moderate, moderate-high, and high.

Significant main effects of time and condition indicate that the intervention appropriately reflects memory decay across time and that the learning condition influenced this loss. The significant interaction found between quartile and time indicates that baseline long-term memory performance influenced word retention across the three free recall assessments (Table 5.2). However, while the high and moderate-high quartiles seem to have experienced more considerable long-term memory loss from the 10-minute to the 24-hour delayed free recall tests observationally (see Figure 5.3 and Figure 5.4 for a graphical representation and Table 5.3 for difference scores by quartile), no interaction in the analytical model indicated statistical significance of a moderating effect of baseline long-term memory performance on the intervention’s outcomes.

Two primary reasons can be referenced as a cause for the findings mentioned above. Either there was no moderating effect, indicating that the intervention protected long-term memory retention regardless of baseline long-term memory functioning, or the sample used in the analysis was too small or too homogenous to detect differences associated with baseline long-term memory quartile. Considering the former point, if memory ability does not influence the effect of the entrained cognitive-motor dual-task, all individuals may be able to reap long-term memory benefits from this type of intervention. Therefore, while the analysis in the present paper did not reject the null hypothesis, it may indicate that entrainment effects are widespread and should be identifiable if the cognitive test used is not bound by the ceiling or floor effects. When the different types of entrainment and their potential for cognitive impact have been discussed in prior literature (Lakatos et al., 2019; Schmid, 2024), the overarching effects of entrainment are generally alluded to as ubiquitous. Moving forward, the potential for widespread benefits from a cognitive-motor dual-task warrants exploration. Future studies should expand these types of analyses to atypical samples, such as children with learning challenges, older adults with mild cognitive impairment, or healthy young adults with attention deficit disorder. Comparatively analyzing different samples may clarify if individual baseline long-term memory differences truly do not impact the mnemonic effects of this type of cognitive-motor entrainment intervention.

In contrast, it is also possible that the analysis failed to identify the underlying moderating effects of individual differences on task performance. Intraindividual difference effects on the relationship between physical activity and cognition have been found in primary (Sibley & Beilock, 2007; Yamazaki et al., 2018) and secondary (Drollette et al., 2014; Ishihara et al., 2020) experimental analyses and through a systematic review and meta-analysis of individual participant data (Ishihara et al., 2021). Furthermore, in a study using a very similar cognitive-motor entrainment intervention, Schmidt-Kassow (2013d)identified an individual differences effect using baseline working memory ability as a distinguishing factor. This robust history of significant intraindividual influence makes the contradictory findings of the present analysis uncharacteristic.

The use of long-term episodic memory as a baseline value for cognitive function may have prevented significant findings. As few moderating analyses rely on this measurement to classify individual differences, implementing different foundational cognitive tests may be more sensitive and effective for these types of classifications. Researchers more commonly use measurements of executive functioning to categorize individuals based on their cognitive prowess, such as working memory  (Schmidt-Kassow et al., 2013d; Sibley & Beilock, 2007; Yamazaki et al., 2018), inhibition (Drollette et al., 2014), cognitive flexibility, or a combination of all three (Ishihara et al., 2021). However, as executive functioning evaluation is much less common in translational settings than long-term memory tests, the use of these variables to categorize or group participants limits their application in the real world. Further research is needed to evaluate how alternative measures of cognitive functioning may differentially moderate the relationship between physical activity and cognition. When selecting cognitive assessments, scientists should consider the practicality of their application in translational settings to support the ease of applying laboratory findings to translational settings in the long run.

The participants who comprised the sample itself may also have limited analytical results. Participants were classified into four quartiles following the precedent set by Sibley and Beilock (2007). However, there is no normative data that can be used to classify individuals based on ModRey free-recall episodic memory retention, which prevents researchers from confirming whether the sample is truly representative of the population. Both experiments included in the analysis used convenience sampling to recruit participants. Most participants were undergraduate or graduate university students who were selectively admitted to the University of Georgia based on their high cognitive abilities. Therefore, the quartiles used to differentiate the sample by long-term memory ability may have been too homogenous to identify differences based on baseline cognitive memory ability. As the effect sizes of individual difference moderation also tend to be smaller, perhaps the sample size used in the present study lacked the necessary power and was unable to identify significant moderating differences due to high levels of variation between measurement points.

Overall, more research is needed to clarify the effects of an entrained cognitive-motor dual-task and to determine how individual cognitive differences may moderate this relationship. Future studies exploring the moderating impact of intraindividual or interindividual cognitive differences should employ safeguards to ensure that the sample recruited is representative of the population, includes children and older adults across a wide range of ages, and well-powered to detect a hypothesized effect. These procedures will help clarify individual difference moderation, the magnitude of the possible effect, and provide clarity regarding the translational application of these laboratory findings. Secondary models or individual participant meta-analyses that combine data from multiple experiments are effective tools that can be used to address these concerns. Additionally, increasing the volume of data included in an analysis will decrease the likelihood that a regression to the mean effect causes significant individual difference outcomes. (Barnett et al., 2004; Schmid, 2024).

## Conclusion

While the absence of a significant moderating individual difference effect failed to support hypotheses, these findings indicate that entraining a cognitive and motor dual-task may enhance cognitive functioning, regardless of foundational long-term memory capabilities.

Although research on this topic is limited (Schmid, 2024), researchers should seek to explore the translational value of these results. By completing future studies that employ cognitive-motor entrainment in a real-world setting, the potentially non-discriminatory cognitive benefits from this type of intervention may be experienced by diverse individuals in various environments.

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# CHAPTER 6

# CONCLUSION

Cognitive-motor entrainment occurs when repetitive, oscillatory excitation patterns between the neural activity underlying motor production and cognitive processing align. This type of entrainment can enhance cognitive processing (Schmidt-Kassow et al., 2013c; Schmidt-Kassow & Kaiser, 2023), decrease motor production variation (Scott et al., 2025), and enhance movement quality (Lakatos et al., 2019) by reducing attentional load and increasing the efficiency of neural network communication. While a variety of experiments report positive cognitive benefits resulting from cognitive-motor entrained dual tasks (Ghai et al., 2018; McIntosh et al., 1997; Schmidt-Kassow et al., 2013b; Schmidt-Kassow & Kaiser, 2023; Schmidt-Kassow et al., 2009; Schmidt-Kassow et al., 2019; Schmidt-Kassow et al., 2023; Schmidt-Kassow et al., 2014; Thaut & Abiru, 2010), further research is needed to integrate findings from different fields studying entrainment's effects, elucidate the nuances of its underlying mechanisms, and explore the potential benefits of its application in various clinical settings and for different populations.

The experiments outlined in Chapter 4 provide promising evidence for the potential benefits of entrainment-based interventions improving cognitive performance, specifically in relation to long-term episodic memory retention. When compared to a traditional dual-task and a sedentary, single-task condition, learning a word list under a cognitive-motor entrained condition (Experiment 1: treadmill walking; Experiment 2: ergometer cycling) consistently leads to significantly higher long-term memory free-recall retention scores immediately, 10-minutes, and 24-hours after exposure. These findings indicate that creating an entrained environment during a cognitive-motor dual task (CMDT) may alleviate cognitive detriments commonly seen during concurrent task production. Contrary to foundational hypotheses, neither physical activity mode (treadmill walking or ergometer cycling) nor foundational long-term free-recall memory capabilities influenced positive long-term memory effects. Therefore, the beneficial mnemonic effects of cognitive-motor entrainment may not be determined by physical activity mode or individual cognitive differences, as previously suggested (Schmid, 2024; Schmidt-Kassow & Kaiser, 2023; Tomporowski & Qazi, 2020).

While basic, laboratory-based research indirectly contributes to the broader scientific corpus, it also lays the groundwork for future discoveries and acts as the cornerstone of scientific advancement, providing the fundamental knowledge base for future discoveries. The findings of basic experiments and secondary analyses, such as those found in Chapters 4 and 5, inform the development of solutions to real-world challenges, driving innovation and improving human lives. The aforementioned cognitive-motor entrainment experiments provide several potential avenues for translation to real-world settings in therapeutic, academic, and everyday environments, which are outlined below.

## Therapeutic Applications

Traditionally, in therapeutic settings, auditory cognitive-motor entrainment has been used to enhance motor output. The cortical proximity of auditory and motor neural networks is thought to contribute to the concurrent synchronization of activation patterns and increase opportunities for neural entrainment between environmental auditory stimuli and efferent motor signals

(Thaut, 2013; Thaut & Abiru, 2010). Practitioners most commonly ask patients to align their motor actions with environmental auditory stimuli, such as rhythmic auditory tones or songs. Experimental results consistently report positive entrainment effects on motor production patterns in patients with neurological disorders, traumatic brain injuries, or who have had a cerebrovascular accident (stroke) (Buhmann et al., 2018; Schaefer et al., 2015; Thaut et al., 2015).

While these therapies have been very successful, they primarily focus on addressing motor production patterns, as cognitive impairments commonly associated with these medical conditions are often left unaddressed. Considering the experimental evidence indicating the positive impacts of cognitive-motor entrainment on cognitive output, applying a similar intervention in the therapeutic setting could support the concurrent rehabilitation of cognitive and motor functions. For example, 30-70% of individuals who have had a stroke experience resultant cognitive impairments (the prevalence depends on the severity of the stroke, the cortical areas involved, comorbidities, etc.) and seek restorative or compensatory therapies (Elendu et al., 2023; Mulhern, 2023). Experimental evidence indicates that CMDT interventions may alleviate dual-task costs that the pathological consequences of a stroke have magnified (Liu et al., 2017; Zhou et al., 2021).  Perhaps asking these patients to engage in an entrained CMDT could increase the efficiency and affordability of rehabilitative therapies by concurrently addressing both issues in one exercise.

Interventions might look like something as simple as asking a participant to synchronize stepping patterns to a metronome as they verbally indicate the varying pitch of the tone heard. Alternatively, participants could be asked to synchronize their walking patterns to a math equation read aloud and asked to answer the problem aloud when a beep was played (see Figure

6.1). Both of these examples of cognitive-motor entrainment interventions would use environmental auditory stimuli to induce voluntary entrainment with motor production output while incorporating a cognitive assessment into the procedure. Task difficulty would likely need to be adjusted based on individual differences.

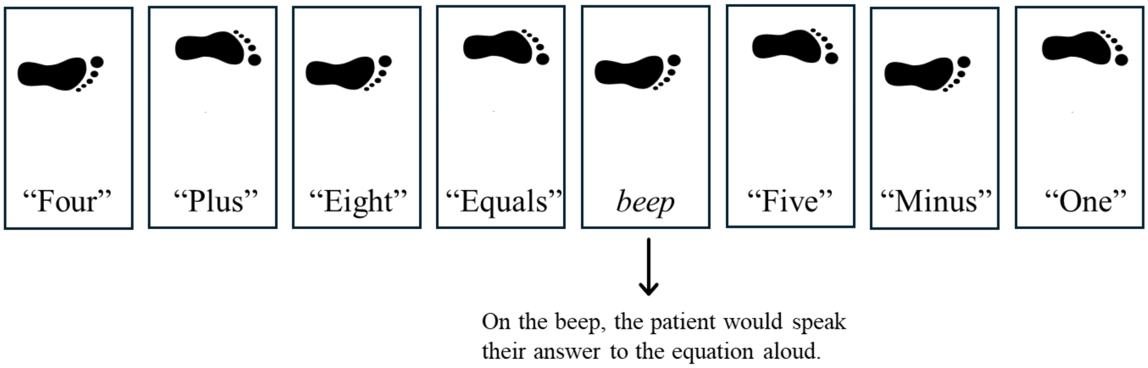

**Figure 6.1** Cognitive-Motor Therapeutic Intervention Example

If successful, a new category of CMDT entrainment interventions might concurrently contribute to the therapeutic recovery of the mind and body. In patients with various neurological diseases, CMDTs have been shown to improve gait stability, reduce falls, and enhance cognition in individuals with Parkinson's Disease (Tan et al., 2024), aid individuals with balance, ambulation, and upper limb functioning post-stroke (Liu et al., 2017; Zhou et al., 2021), enhance motor skill development, executive functioning, and attentional processes in individuals with traumatic brain injuries, and protect older adults from cognitive and motor declines commonly associated with aging or Alzheimer's Disease (Fritz et al., 2015). By integrating voluntary or involuntary entrainment into modern CMDT therapeutic techniques, the existing benefits may have the opportunity to be magnified, increasing their positive impact. Further research is needed to investigate these hypotheses, evaluate the practicality of the proposed techniques, and determine how to accommodate individual proficiency differences.

## Academic Applications

Incorporating cognitive-motor entrainment into the classroom setting may also lead to positive psychological and physiological benefits due to its potential to enhance long-term episodic memory retention while providing opportunities for children to be physically active during the mostly sedentary school day. In the past two decades, there has been a substantial push to evaluate the effects of classroom-based physical activity engagement on cognitive functioning and academic success, with results generally indicating a small but positive association between these variables (Donnelly et al., 2016; Donnelly & Lambourne, 2011). Much of this research involves children in preschool, elementary school, and middle school due to higher levels of flexibility in the academic environment.

The theory of embodied cognition provides a rationale for much of this research by arguing that our thoughts and emotions are influenced by our physical body and its interaction with the surrounding environment (Shapiro, 2011). When incorporating physical activity into an academic setting, embodied cognition theory is most commonly represented by gestural or gross motor movements by which the unconscious creation of enhanced mental representations is thought to occur during encoding, expanding the parameters of an individual's cognitive capacity (Mavilidi et al., 2021). Experiments evaluating the use of embodied cognition, where physical activity is intertwined with cognitive training, have primarily addressed memory effects, and two prominent reviews affirm its positive mnemonic benefits (Mavilidi et al., 2018; Skulmowski & Rey, 2018). Considering the statistically significant positive effects found from learning a word list under an entrained CMDT condition in Chapter 4's Experiments 1 and 2, creating an entrained embodied cognition learning intervention may lead to larger summative effects or even gestalt enhancements when these techniques are combined.

A simple way that an entrained CMDT could be used in an academic setting would be to implement walking or marching during choral reading, a reading technique used to enhance fluency (McCauley & McCauley, 1992; Paige, 2011). During choral reading, students read words aloud in unison to a rhythmic pattern. Suppose students marched around the room to the beat of the reading pattern. In that case, this simple addition may enhance their cognitive processing abilities, provide opportunities for physical activity during the school day, and maintain student engagement. Alternatively, cognitive-motor entrainment could be used in mathematics to help students remember multiplication tables. Often, students struggle with rote memorization of multiplication tables, and techniques such as singing the numbers to the beat of a song enhance information retention (Greene, 1992; Yasin et al., 2017). Perhaps aligning multiplication tables with oscillatory actions and rhythmic patterns would support students' learning and help them retain the appropriate information in their long-term memory. It is important to note that synchronization does not induce true cognitive-motor entrainment. Instead, cognitive stimulation and motor production patterns must remain in continuous oscillatory patterns (Bittman, 2021). Therefore, songs should be selected with care and in regard to the beat, as simply aligning words with the melody of a song would not necessarily induce CMDT entrainment.

## Commonplace Applications

While the applications of an entrained CMDT listed above are promising, they only provide support to a particular subset of the population. Therefore, considering how the application of an entrained CMDT could be used in an everyday setting may also provide unique insight into the translational merit of the experimental findings identified in Chapters 4 and 5. To support the ease of implementation of a dual-task entrainment intervention, identifying a pre-established physical environment, social environment, or piece of technology that would be most conducive to implementing cognitive-motor entrainment is essential.

Perhaps the most straightforward movement-tracking device with the promise to induce cognitive-motor entrainment is the smartphone. With built-in pedometers, smartphones continually track an individual’s stepping patterns. If apps were designed to process this information in real-time and entrain stepping patterns with information presentation, an easy solution to induce cognitive-motor entrainment would always be available. Consider language learning apps such as Duolingo (Duolingo, 2011) or Babbel (GmbH, 2007). Language information is either visually or audibly presented, and individuals are asked to repeat that information or retain it for later testing. Suppose an extension to these apps was created to entrain information presentation over headphones with the walking patterns of an individual. In that case, the learner may engage in physical activity by walking around a room, on a treadmill, or outside as they are studying a language, creating a cognitive-motor entrainment environment in which the individual may be able to reap the mnemonic benefits of this particular dual task.

Taking this idea a step further, perhaps virtual reality simulations could create immersive learning experiences that are also conducive to cognitive-motor entrainment, providing a gamification extension to this theoretical concept (Greene, 1992). The product would likely make the immersive learning experiences more fun and engaging while creating an entrained environment that holds the potential to enhance long-term memory retention over time. Additionally, this type of approach has the potential to benefit individuals of all ages and to be scaled to the individual's learning level.

## Conclusion

While abstract, the concepts proposed above, implementing cognitive motor entrainment into the therapeutic, academic, and everyday environment, exemplify how the basic conclusions identified in Chapter 4’s experiments have translational merit. By incorporating physical activity into cognitive assessments and creating an entrained environment, dual tasks may have the potential to enhance cognitive output and avoid producing dual-task costs commonly associated with concurrent task production. Much more research is needed to understand the feasibility of the propositions mentioned above, the practicality of entrained dual-task creation, the magnitude of the benefits provided, and how the public and everyday learners would respond to this alternative strategy.

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# APPENDIX A

*24 Hour Health History Assessment*

Participant ID: ________________________

24-Hour History Questionnaire
Date Administered: ________________
Session #: 1 / 2 / 3 / 4 / 5 / 6 / 7 (Circle)
Time: ________________
1. How much sleep did you get last night? (please circle one)
1 to 4 hrs / 4 to 6 hrs 6 to 8 hrs / 8 to 10+ hrs
2. How much sleep do you normally get each night? (please circle one)
1 to 4 hrs / 4 to 6 hrs 6 to 8 hrs / 8 to 10+ hrs
3. When did you last have (and amount):
    Coffee: ____________ _________
    Tea : ____________ _________
    Soft drink: _____________ __________
    Drugs (including aspirin): ____________ _________
    Alcohol: __________ _________
4. What sort of physical activity did you perform yesterday?
5. What sort of physical activity have you performed today?
6. Describe your general feelings by checking **one** of the following:
_______ excellent
_______ very good
_______ good
_______ neither good or bad
_______bad
_______ very bad
_______ terrible

*Medical History Assessment*
***Date administered*__________**
Sex ______________ Age ____________ Date of Birth _________
1. Do you have or have you ever had: (check if yes)
_____ Pain in your heart or chest
_____ Heart attack
_____ Rheumatic fever (Recent)*
_____ Diseases of the arteries
_____ Varicose veins
_____ Heart murmur (Recent)
_____ Any heart problem
_____ Abnormal EKG
_____ Extra or skipped heart beats
_____ Phlebitis
_____ Dizziness or fainting spells
_____ Back pain (Recent)
_____ Swollen, stiff or painful joints
_____ Arthritis of arms or legs
_____ Scarlet fever
_____ Liver disease
_____ Hypothyroidism
_____ Coughing of blood
_____ Anemia
_____ Diabetes
_____ Epilepsy (Recent)
_____ Bronchitis
_____ Asthma (Recent)
_____ Pneumonia (Recent)
_____ Abnormal chest x-ray
_____ Other lung diseases
_____ Injury to back/arm/legs/joints(recent)
_____ Stroke
_____ High blood pressure
_____ Badly swollen ankles
_____ Cough on exertion (Recent)
_____ Sickle cell trait/disease
_____ Kidney disease
_____ Operations (Recent)
_____ Heat-related illness (severe muscle cramps, heat exhaustion, heat stroke)
* Recent = within the past 12 months
Explanation or comments:
______________________________________________________________________________
______________________________________________________________________________
2. List any medicines, drugs, and herbal products or dietary supplements you are now taking:
______________________________________________________________________________
______________________________________________________________________________
3. Date of last complete medical exam: __________ Were results normal? _________
If no, explain: __________________________________________________________________
4. Explain any other significant medical problems you consider it important for us to know:
______________________________________________________________________________
______________________________________________________
5. Have you been diagnosed with a Learning Disability?
Yes ____ No _____
If yes, explain: _______________________________________________________
6. Have you been diagnosed with a Attention Disorder?
Yes ____ No _____
If yes, explain: _______________________________________________________
7. Do you have any visual problems? e.g., are you nearsighted (Myopic)?
Yes _____No _____
If yes, explain: __________________________________________________________
8. What is your dominant hand? Right ______ Left _____ Ambidextrous _________
9. Are you pregnant?
Yes _____No _____

*Godin Leisure-Time Exercise Questionnaire*

Considering a **7-Day period** (a week), how many times on the average do you do the following kinds of exercise for **more than 15 minutes** during your **free time** (write on each line the appropriate number). **TIMES PER WEEK**

a) **STRENUOUS EXERCISE (HEART BEATS RAPIDLY)** (i.e. running, jogging, hockey, football, soccer, squash, basketball, cross country skiing, judo, roller skating, vigorous swimming, vigorous long distance bicycling)

b) **MODERATE EXERCISE (NOT EXHAUSTING)** (i.e. fast walking, baseball, tennis, easy bicycling, volleyball, badminton, easy swimming, alpine skiing, popular and folk dancing)

c) **MILD EXERCISE (MINIMAL EFFORT)** (i.e. yoga, archery, fishing from river band, bowling, horseshoes, golf, snow-mobiling, easy walking

| | ***Exercise Interest Development Scale Questions*** | Do Not Agree At All | Very Slightly Agree | Slightly Agree | Moderately Agree | Mostly Agree | Strongly Agree | Very Strongly Agree |
|---|---|---|---|---|---|---|---|---|
| 1 | I seek out opportunities to engage in exercise. | **1** | **2** | **3** | **4** | **5** | **6** | **7** |
| 2 | I look forward to the next time I'll be able to engage in exercise. | **1** | **2** | **3** | **4** | **5** | **6** | **7** |
| 3 | I am not easily distracted when I engage in exercise. | **1** | **2** | **3** | **4** | **5** | **6** | **7** |
| 4 | I pursue exercise on my own time. | **1** | **2** | **3** | **4** | **5** | **6** | **7** |
| 5 | I generate questions about exercise. | **1** | **2** | **3** | **4** | **5** | **6** | **7** |
| 6 | I see myself engaging in exercise for a long time to come. | **1** | **2** | **3** | **4** | **5** | **6** | **7** |
| 7 | Exercise is meaningful to me. | **1** | **2** | **3** | **4** | **5** | **6** | **7** |
| 8 | I become more interested the more I engage with exercise. | **1** | **2** | **3** | **4** | **5** | **6** | **7** |
| 9 | I often have questions about exercise. | **1** | **2** | **3** | **4** | **5** | **6** | **7** |
| 10 | I pursue exercise for my own reasons. | **1** | **2** | **3** | **4** | **5** | **6** | **7** |
| 11 | I pursue exercise even though no one makes me do it. | **1** | **2** | **3** | **4** | **5** | **6** | **7** |
| 12 | When I set goals related to exercise, I stick to them. | **1** | **2** | **3** | **4** | **5** | **6** | **7** |
| 13 | I try to schedule my time so that I can engage in exercise. | **1** | **2** | **3** | **4** | **5** | **6** | **7** |
| 14 | Exercise is an important interest to me. | **1** | **2** | **3** | **4** | **5** | **6** | **7** |
| 15 | I want to know more about exercise. | **1** | **2** | **3** | **4** | **5** | **6** | **7** |
| 16 | I enjoy exploring questions within exercise. | **1** | **2** | **3** | **4** | **5** | **6** | **7** |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 17 | I have respect for exercise. | **1** | **2** | **3** | **4** | **5** | **6** | **7** |
| 18 | Exercise has value to me. | **1** | **2** | **3** | **4** | **5** | **6** | **7** |
| 19 | I am able to guide my own learning about exercise. | **1** | **2** | **3** | **4** | **5** | **6** | **7** |
| 20 | I find the resources I need to continue to engage in exercise. | **1** | **2** | **3** | **4** | **5** | **6** | **7** |

V. *Situational Interest Survey*

TRIQ 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 task 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 task?

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

3. I think the task was very interesting.

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

Please rate what you think about the activity you just completed.

(1= Strongly disagree, 4 = neutral, 7= Strongly agree)

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| 1. This activity was exciting | | | | | | | |
| 2. It was a complex activity | | | | | | | |
| 3. The activity was complicated | | | | | | | |
| 4. My attention was high while doing the activity | | | | | | | |
| 5. This activity was interesting | | | | | | | |
| 6. I was very attentive all the time while doing the activity | | | | | | | |
| 7. I'd like to find out more about how to do it | | | | | | | |
| 8. This is an exceptional activity | | | | | | | |
| 9. I want to analyze it to have a grasp on it | | | | | | | |
| 10. This activity was appealing to me | | | | | | | |
| 11. The activity was fun to me | | | | | | | |
| 12. This was a new-fashioned activity for me to do | | | | | | | |
| 13. It was an enjoyable activity to me | | | | | | | |
| 14. I want to discover all the tricks in this activity | | | | | | | |
| 15. This activity was fresh | | | | | | | |
| 16. This activity was new to me | | | | | | | |
| 17. I was focused while doing the activity | | | | | | | |
| 18. I was concentrated while doing the activity | | | | | | | |
| 19. It was fun for me to try this activity | | | | | | | |
| 20. This activity was a demanding task | | | | | | | |
| 21. This was an interesting activity for me to do | | | | | | | |
| 22. The activity inspired me to participate | | | | | | | |
| 23. It was hard for me to do this activity | | | | | | | |
| 24. I'd like to inquire into details of how to do it | | | | | | | |

# APPENDIX B

*ModRey Word Lists (Hale et al., 2019)*

ModRey A: Bell, Coffee, Color, Curtain, Drum, Farmer, Garden, Ham, Hat, House, Moon, Nose, Parent, River, Scarf, School, Suitcase, Tree, Turkey, Violin

ModRey B: Bird, Boat, Church, Cloud, Cousin, Desk, Dog, Earth, Fish, Glasses, Gun, Knife, Lamb, Mountain, Pencil, Ranger, Shoe, Stair, Stove, Towel

# APPENDIX C

## *Experimental Word Lists*

The word lists listed below were generated following methods used in Loprinzi et al. (2023) and originating from the MRC Psycholinguistic Database (Wilson, 1988).

List 1: Basement, Beach, Bible, Black, Brain, Cabin, Cheese, Chief, Children, China, Chocolate, Clown, Color, Doctor, Flame, Football, Glass, Gorilla, Honeymoon, Lawyer, Magazine, Morning, Plate, Pollution, Quarter, River, Scotch, Snake, Soccer, Spice, Stable, Stomach, Student, Teacher, Tennis, Trail, Valley, Vodka, Walnut, Woman

List 2: Blonde, Bounce, Candy, Capital, Circle, Country, Dancer, Dress, Eagle, Entrance, Estate, Flood, Forest, Green, Guest, Hurricane, Light, Metal, Mirror, Music, Novel, Photograph, Priest, Prince, Pudding, Rifle, Resort, Rough Sandal, Slope, Smell, Stick, Storm, Swimming, Teeth, Telephone, Tomato, Troop, Whiskey, World

List 3: Author, Battle, Blood, Blossom, Bread, Camera, Church, Crown, Dance, Father, Grave, Indian, Instrument, Jewel, Limousine, Mansion, Mattress, Onion, Organ, Paper, Piano, President, Property, Queen, Reptile, Rocket, Shirt, Square, Spring, Strawberry, Stone, Thunder Trash, Village, Voter, Walking, Weight, Whale, Wheel

# APPENDIX D

## *Preferred Walking Speed Protocol*

### Test preparation:

Prepare Participant for Preferred Walking Speed (PWS) protocol

Preliminary Instructions/Introduction to study: "During today's session, we will be determining your preferred walking speed. In order to determine to PWS, you will wear a pair of nonresistant slippers while walking on the treadmill. Before we begin, I would like you to select a pair of slippers that you feel comfortable wearing."

- different sizes available, select the most appropriate size and insert matching Noraxon insoles

"Please put on these shoes. After you do so, I will connect gait sensors to the bottom of your shoe; one of the sensors will be attached to your heel and one will be attached to your toe. We will also Velcro-strap the wires to your legs (just below the tibial tuberosity). Is this okay?"

"Preferred walking speed refers to a "*comfortable walking speed*." Imagine what speed you use to walk around your house; this would be classified as your PWS. Please try to walk around the lab at this speed now. Sometimes, we think we should be moving at faster paces while on a treadmill because many people associate them with higher-intensity exercise. To account for this, please try to take note of your pacing now. We will ask you to try to identify this same pace on the treadmill."

Foot Sensor Placement Protocol

- Have participants select a slipper that matches their foot size.
- Input the appropriate noraxon insoles
- Record which size was selected on data collection sheet
- Place the Noraxon sensors on the Participant's ankles and attach the sensors to the insoles. Use the flexi wraps to secure the sensor in place.
- Ask the Participant to stand and confirm nothing is uncomfortable or too tight.
- Ask the Participant to step up onto the treadmill.
- Adjust the cord that connects the foot sensors. There should be enough slack to allow the Participant to walk but not so much that the cords get in the way during the swing phase or become a tripping hazard.

As you are following these steps, vaguely explain what each piece does to provide comfort and ease nerves.

Instructions:

"Before you step onto the treadmill, I will describe how we will assess your preferred walking pace. You will first perform one familiarization trial, followed by four assessment trials. The total walk time will be approximately 20-30 minutes."

"During the familiarization trial, the treadmill's speed will start at a slow speed for 15 seconds. I will gradually increase the treadmill speed every 15 seconds to a terminal speed before decreasing the treadmill speed back down to the starting speed. Pay attention to the speeds of the treadmill, as you will be asked to indicate your preferred speed in the next trials."

"During the 2nd and 3rd trials, I will repeat this procedure of starting at a slow speed for 15 seconds, and gradually increasing and then decreasing the speed. Please tell me when you have reached your preferred walking speed as the speed increases."

"During the 4th and 5th trials, you will repeat this procedure. However, this time, you will adjust the treadmill's speed based on your preference, gradually increasing the speed until you reach your preferred walking speed. You can increase or decrease the speed of the treadmill at any rate. There will be a 15 second rest period between each trial."

"Do you have any questions?"

"Before we start, I am going to calibrate our gait analysis system to match your unique weight distribution."

- Follow the Noraxon program prompts to calibrate. More information is in the Noraxon set-up section above, if needed.

"Please stand on the rails on each side of the treadmill belt and hold on to the support arms. The researcher will start the treadmill and tell you when to step onto the moving belt and begin walking. As you walk, please keep your hands down at your side."

- Plug in cable BioPac
- Confirm heart rate measurements are transmitted to watches

*Directions*: Note at which speed the participant indicates PWS. Input speed into the Google sheet across each trial. The average speed will be calculated by the data sheet's embedded formulas.

**Trial 1 - Familiarization (researcher controlled):**

While the Participant is standing on the side of the treadmill, start the treadmill at 1.0 mph. Ask participants to step on the moving belt and grasp the handrail. Begin protocol and take participants through ascending and descending measures. The Participant WILL NOT indicate PWS during this trial; this trial serves as familiarization.

Instructions for Participant: "We will now begin the familiarization trial. Pay attention to the speed of the treadmill. You will be asked to indicate PWS in the next trials. Please wait until I tell you to step on to and off of the treadmill. Are you ready?"

Start: 15 secs @ 1.0 mph; 15 secs @ 1.2 mph; 15 secs @ 1.4 mph; 15 secs @ 1.6 mph; 15 secs @ 1.8 mph; 15 secs @ 2.0 mph; 15 secs @ 2.2 mph; 15 secs @ 2.4 mph; 15 secs @ 2.6 mph; 15 secs @ 2.8 mph; 15 secs @ 3.0 mph; 15 secs @ 2.8 mph; 15 secs @ 2.6 mph; 15 secs @ 2.4 mph; 15 secs @ 2.2 mph; 15 secs @ 2.0 mph; 15 secs @ 1.8 mph; 15 secs @ 1.6 mph; 15 secs @ 1.4 mph; 15 secs @ 1.2 mph; 15 secs @ 1.0 mph.

MARK PWS; 15 second break!

**Trial 2 – Assessment 1 (researcher controlled):**

Repeat the protocol, but this time, the Participant will indicate when PWS has been reached. Start the treadmill at 1.0 mph. Once the PWS has been reached, continue increasing the treadmill speed in increments of .2 mph as before. After you hit 3 mph, decrease the treadmill speed in increments of .2 mph, leaving 5 seconds in between each stage until 1.0 mph is reached.

Instructions for Participant: "We will now begin the 1st assessment trial. As the treadmill speed increases, indicate verbally when you reach your PWS. Please wait until I tell you to step on to and off of the treadmill. Are you ready?"

MARK PWS

Start: 15 secs @ 1.0 mph; 15 secs @ 1.2 mph; 15 secs @ 1.4 mph; 15 secs @ 1.6 mph; 15 secs @ 1.8 mph; 15 secs @ 2.0 mph; 15 secs @ 2.2 mph; 15 secs @ 2.4 mph; 15 secs @ 2.6 mph; 15 secs @ 2.8 mph; 15 secs @ 3.0 mph; 5 secs @ 2.8 mph; 5 secs @ 2.6 mph; 5 secs @ 2.4 mph; 5 secs @ 2.2 mph; 5 secs @ 2.0 mph; 5 secs @ 1.8 mph; 5 secs @ 1.6 mph; 5 secs @ 1.4 mph; 5 secs @ 1.2 mph; 5 secs @ 1.0 mph.

MARK PWS; 15 second break!

**Trial 3 – Assessment 2 (researcher controlled):**

Repeat the protocol listed for trial 2.

Instructions for Participant: "We will now begin the 2nd assessment trial. As the treadmill speed increases, indicate verbally when you experience your PWS. Are you ready?"

Start: 15 secs @ 1.0 mph; 15 secs @ 1.2 mph; 15 secs @ 1.4 mph; 15 secs @ 1.6 mph; 15 secs @ 1.8 mph; 15 secs @ 2.0 mph; 15 secs @ 2.2 mph; 15 secs @ 2.4 mph; 15 secs @ 2.6 mph; 15 secs @ 2.8 mph; 15 secs @ 3.0 mph; 5 secs @ 2.8 mph; 5 secs @ 2.6 mph; 5 secs @ 2.4 mph; 5 secs @ 2.2 mph; 5 secs @ 2.0 mph; 5 secs @ 1.8 mph; 5 secs @ 1.6 mph; 5 secs @ 1.4 mph; 5 secs @ 1.2 mph; 5 secs @ 1.0 mph.

MARK PWS; 15 second break!

**Trial 4 – Assessment 3 (Participant controlled):**

Start the treadmill at 1.0 mph. Have participants increase/decrease treadmill speed, ensuring the Participant cannot see the treadmill screen, but you can.

Instructions: "We will now begin the 3rd assessment trial. This time, I will ask you to gradually increase the speed of the treadmill until your PWS is reached. Press the up and/or down arrows to change the speed. You may increase or decrease the speed of the treadmill until your PWS is reached. Please indicate verbally when you have reached your PWS. Please wait until I tell you to step onto and off of the treadmill. Are you ready?"

After they reach their PWS, slowly decrease the treadmill speed in .2mph/5 second increments back to 1mph.

MARK PWS; 15 second break!

**Trial 5 – Assessment 4 (Participant controlled):**

Instructions: "We will now begin the 4th assessment trial. I will once again ask you to gradually increase the speed of the treadmill until your PWS is reached. You may increase or decrease the speed of the treadmill until your PWS is reached. Please indicate verbally when you have reached your PWS. Please wait until I tell you to step onto and off of the treadmill. Are you ready?"

MARK PWS

Preferred walking pace

Total preferred walking speed = PWS T2 _____ + PWS T3 _____ + PWS T4 _____ + PWS T5 = _____

Average preferred walking speed = total preferred walking speed _____ / 4 = _____ mph

Baseline Walking Protocol

"Now that we have calculated your preferred walking pace, we will ask you to walk quietly on the treadmill at that speed for 5 minutes to establish some baseline data. You will also be asked to report your RPE at the end of the session."

Input HR (each minute) and RPE values directly into the Excel sheet.

Do not talk to the participant during the five-minute baseline.

Following practice/assessment:

*"Thank you for your participation in assessing your PWS. In a later session, we will ask you to walk on the treadmill for approximately 20 minutes at your preferred walking speed. Please confirm that you can walk comfortably at your preferred pace for 20 minutes."*

### *Preferred Cycling Intensity Protocol*

Bike Preparation

Establish the preferred settings for the participant for the cycle ergometer. Record in the datasheet.

1. Seat height
2. Seat distance
3. Handlebar height
4. Handlebar distance

Ensure the Wahoo Cycling Cadence sensor on the bike is connected to the cloud for measurements throughout the protocol.

Test preparation:

Prepare participants for cycling intensity protocol.

Preliminary Instructions/Introduction to study: "During today's session, we will be determining your preferred cycling intensity that will be used in testing sessions moving forward. You will be asked to indicate when you have reached an RPE of 9 as we increase the bike’s resistance. Please be as honest as you can and answer purely based on your own perceptions of how hard you are working. *During all trials, please maintain a constant cycling cadence by completing one full foot rotation per beat that you will hear on the metronome playing aloud.*

During the first trial, we will start the cycle at a baseline resistance and slowly increase the cycle to a terminal resistance. During this trial, continue to pedal as you feel a range of cycling intensities."

- Start the metronome.
- Begin protocol at 10 W, increase in 30 sec increments of 5 W until you get to 50 W.
- Reset the ergometer to 10 W before starting the next trial.

"During the next three trials, I will slowly increase the treadmill's resistance. When you feel like you are at an RPE of 9, please indicate this aloud."

- Start at 10 W, increase in 30 sec increments of 10 W until the participant indicates that they have reached a RPE of 9. If they say they are between two RPE numbers, increase or decrease the treadmill by 5 W and have them cycle at this new interval for 30 seconds.
- Once they are confident they are at a RPE of 9, decrease the treadmill to 10 W, have them cycle for 30 seconds and repeat this process two more times
- Record the wattage for each trial on the run sheet and in the data sheet online.
- Calculate the average of all 3 reported wattages to establish the cycling wattage moving forward.

Baseline Cycling Protocol

"Now that we have calculated your preferred cycling intensity, we will ask you to cycle at this intensity for 5 minutes to establish baseline data. You will also be asked to report your RPE at the end of the session."

Input HR (each minute) and RPE values directly into the Excel sheet.
Do not talk to the Participant during the 5-minute baseline!

Following practice/assessment:
*"Thank you for your participation in assessing your preferred cycling intensity. Please confirm that you will be able to cycle comfortably at this intensity for 20 minutes."*

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