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The Effects Of Acute Exercise On Postural Control, Information Processing, Motor Skill Acquisition, And Executive Function

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THE EFFECTS OF ACUTE EXERCISE ON POSTURAL CONTROL, INFORMATION PROCESSING, MOTOR SKILL ACQUISITION, AND EXECUTIVE FUNCTION

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DEDICATION

This work is dedicated to my wife and best friend, Alexandria Kendall, for her unwavering love, support, patience, and encouragement during the past four years. It is also dedicated to my best little buddy, Ezekiel James, who is far and away my greatest accomplishment and deepest joy. And finally, to my father, mother, and sister, who have provided constant encouragement and support throughout my entire life. I would not be where I am or who I am without you all.

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CHAPTER 1: INTRODUCTION

Physical movement is critical to the way in which human beings interact with the world and with each other. So critical, in fact, that preservation of the ability to move efficiently is a major component of optimum aging (Rowe & Kahn, 1997). It is clear that both cognitive and physical factors contribute to the human capacity for movement. Some researchers have even postulated that human cognitive abilities evolved for the primary purpose of generating the physical movement necessary for survival (Schmidt & Lee, 2011). Given the intrinsic importance of human movement, the development of a deeper understanding of how movement is controlled, learned, and optimized has important implications for the maximization of basic human functioning, rehabilitation, and athletic performance.

Effective and purposeful human movement is dependent on the ability of the central nervous system (CNS) to integrate and utilize a vast array of sensory information obtained by the peripheral nervous system (PNS) (Groenewegen, 2003; Horak, 1997). The ability of the CNS to learn, to coordinate, and to control movement is essential for both highly technical movements involved in athletic maneuvers and for simple motor tasks involved in the most basic human functioning, such as walking and maintaining appropriate posture (Schmidt & Lee, 2011). Moreover, acquisition of new motor skills is essential across the human lifespan. Critical to the concepts of both motor control (the process by which the cognitive capacities of the brain activate and coordinate muscle actions for a particular motor skill) and motor learning (the complex cognitive processes which occur in the brain as a result of practice or experience which allow for the acquisition of a new motor skill) is the underlying assumption that the completion of a purposeful movement relies on synchronization of the CNS, the PNS, and the muscular system (Brooks, 1983). Deficits in motor ability can similarly be explained by dysfunction in one of these systems (Seidler et al., 2010). When studying motor control and learning, therefore, it is crucial to include observation of each of these contributing components (Montero□Odasso, Verghese, Beauchet, & Hausdorff, 2012; Ringsberg, Gerdhem, Johansson, & Obrant, 1999; Salthouse, 1993; Yogev□Seligmann, Hausdorff, & Giladi, 2008).

There is an expanding volume of literature focusing on various strategies to improve the efficiency of motor control by priming the nervous system before the execution of a task (Schabrun & Chipchase, 2012; Warraich & Kleim, 2010). Priming is accomplished by an activity that either increases cortical excitability (which may coincide with improved motor function) or facilitates cognitive processing leading to neuroplasticity and allowing for the formation of new motor behaviors (Stoykov, Corcos, & Madhavan, 2017; Stoykov & Madhavan, 2015; Ward & Cohen, 2004). Pharmacologic trials, non-invasive brain stimulation, and sensorimotor interventions (e.g., whole-body vibration training) have all been subjects of investigation and have been found to hold the potential to prime the CNS and to improve cognitive function and motor behaviors (Dockery, Hueckel-Weng, Birbaumer, & Plewnia, 2009; Flöel, Rösser, Michka, Knecht, & Breitenstein, 2008; Rees, Murphy, & Watsford, 2009; Reis et al., 2008; Rosenkranz & Rothwell, 2012; Stoykov & Madhavan, 2015). Studies examining these strategies have demonstrated success in improving motor function, but the techniques all have practical limitations given their expense and difficulty to perform in rehabilitative and athletic training settings.

A more sensible rehabilitative method to prime the brain and improve motor control and motor learning is movement-based priming (Byblow et al., 2012). Movement-based priming may involve mirror symmetric (active or passive) movements such as arm-swinging or unilateral/bilateral movements like pedaling (Stoykov & Madhavan, 2015; Yamaguchi, Fujiwara, Liu, & Liu, 2012). Movement-based priming requires movement of a specific limb or limbs before the execution of a particular motor task. Movement before or during motor training is thought to increase neural activity and facilitate mechanisms such as long-term potentiation which may improve both the acquisition and retention of new motor skills (Stoykov et al., 2017). Previous investigation of movement-based priming suggest that it is a viable option to prime the brain and improve motor control, but, to date, it remains underexplored (Stinear, Barber, Coxon, Fleming, & Byblow, 2008; Stoykov, Lewis, & Corcos, 2009).

Research has only recently explored exercise as a method of priming the brain. Exercise has been found to elicit similar physiologic responses (e.g., improved cortical excitability and increased brain plasticity) to the above-mentioned pharmacologic and sensorimotor interventions (Mang, Brown, et al., 2016; Mang, Campbell, Ross, & Boyd, 2013; Mang, Snow, Campbell, Ross, & Boyd, 2014). These effects have been observed in both healthy and clinical populations, suggesting that acute aerobic exercise has potential as a means to prime the brain and improve motor skill acquisition and retention (Hirsch &

Farley, 2009). Still, the actual effect of exercise on motor control and motor learning has not been thoroughly explored (Basso & Suzuki, 2017; Stoykov & Madhavan, 2015).

Despite the paucity of research exploring the effect of exercise on motor control and motor learning, it is widely accepted that acute and chronic exercise is associated with improved cognitive functioning (Basso & Suzuki, 2017; Ludyga, Gerber, Brand, Holsboer□Trachsler, & Pühse, 2016b; Tomporowski, 2003). Research has demonstrated that exercise improves information processing, attention, and the efficiency of a number of executive functions (EFs) such as mental flexibility, planning, and cognitive control (Audiffren, Tomporowski, & Zagrodnik, 2008, 2009; Chang, Labban, Gapin, & Etnier, 2012; Davranche, Burle, Audiffren, & Hasbroucq, 2005; Tomporowski, 2003). Additionally, researchers have highlighted that improvements in learning-orientated tasks may be a direct result of improved cognitive abilities (Lambourne & Tomporowski, 2010; McMorris & Hale, 2012). Given the essential role higher-order cognitive functions are now known to play in motor control and motor learning, this research minimally suggests that exercise may enhance motor learning and motor control via its effects on cognition (Mirelman et al., 2012; Yogev□Seligmann et al., 2008).

One limitation of the aforementioned body of literature is that most studies have examined the effect of exercise on cognitive functions primarily attributed to the prefrontal cortex (PFC) (Basso & Suzuki, 2017; Singh & Staines, 2015). The impact of exercise on other regions of the brain, particularly its direct effects on the motor cortex, warrants further investigation. Preliminary studies have demonstrated that exercise can elicit similar physiologic responses in the motor cortex (e.g., increased brain plasticity, excitability, and improvement in primary motor cortex inhibition) to those seen in the PFC (McDonnell, Buckley, Opie, Ridding, & Semmler, 2013; Mooney et al., 2016). However, the vast majority of current literature has focused only on evaluating these physiologic alterations, paving the way for future research aimed at understanding the effect of exercise on objective behavioral measures of motor function such as postural control or motor skill acquisition (Basso & Suzuki, 2017).

As a whole, the established evidence exploring the effects of exercise on postural control is quite new. In older adults, researchers have reported that moderate physical activity and acute exercise to fatigue results in reduced postural control (Egerton, Brauer, & Cresswell, 2009; Moore, Korff, & Kinzey, 2005). Similar findings have been reported in younger adults (Fox, Mihalik, Blackburn, Battaglini, & Guskiewicz, 2008; Guidetti, Franciosi, Gallotta, Emerenziani, & Baldari, 2011). The evidence further suggests that, when too fatiguing, exercise negatively impacts stability and motor function by altering sensory inputs (Helbostad et al., 2010; Paillard, 2012). However, postural stability appears to recover quickly in healthy adults, with all negative impact resolving within 10-15 minutes of exercise cessation. The recent focus of research has been to investigate how fatiguing exercise impacts postural control and motor function. It remains unclear if exercise followed by adequate recovery can serve as a priming mechanism for the nervous system and lead to improved postural control.

Only a few studies have examined the effects of acute exercise on motor skill acquisition and motor learning, in addition to its effects on gross motor functions like postural control (Mang et al., 2014; Roig, Skriver, Lundbye-Jensen, Kiens, & Nielsen, 2012; Statton, Encarnacion, Celnik, & Bastian, 2015). The findings from these studies suggest that a single bout of exercise improves motor abilities according to parameters such as sequence-specific implicit motor learning, motor skill acquisition, and motor skill retention. However, other studies have found that an acute bout of moderate intensity exercise may only impact motor learning when learning is measured by delayed retention and/or transfer tests (Mang et al., 2014; Roig et al., 2012; Snow et al., 2016). Overall, despite the limited evidence, it appears that acute exercise can improve motor skill acquisition and retention and that inconsistent findings may be more related to variables like the specific motor task utilized, when skill acquisition was assessed, and exercise intensity. Given the mixed preliminary findings, additional research is needed to clarify the impact of acute exercise on motor skill acquisition and motor learning (Statton et al., 2015).

Due to the limited number of studies investigating the acute effects of exercise, research is also needed to understand how various modes and qualities of exercise may uniquely impact motor control and motor learning. In previously mentioned studies, Mang et al. (2014) and Roig et al. (2012) both had participants perform a similar warm-up and exercise session lasting 20 minutes on a cycle ergometer. Participants alternated between 3-minute periods of high-intensity cycling (90% of max workload) and 2-minute periods of lower intensity cycling (50 watts). Statton et al. (2015) had participants perform 30-minutes of moderate-intensity exercise on a treadmill with the goal of keeping subjects' heart rates between 65-85% of their age-predicted max heart rate. These studies all demonstrated that moderate-vigorous aerobic exercise (walking and cycling) improves motor learning. The effects of other exercise modalities beyond walking and cycling have received little attention, however, and need to be formally investigated.

High-intensity interval training (HIIT) has gained widespread appeal due to its numerous physiologic benefits and its time efficiency (Gibala & McGee, 2008). HIIT is considered safe, cost-effective, and has been successfully incorporated as a major component of rehabilitation programs for higher-risk clinical populations (Guiraud et al., 2012; Meyer, Gayda, Juneau, & Nigam, 2013; Pattyn, Coeckelberghs, Buys, Cornelissen, & Vanhees, 2014). Despite its prevalence and the sound data demonstrating the physiologic benefits of HIIT, only a few studies have specifically assessed the effects of HIIT on executive function, motor control, motor learning, and other relevant cognitive processes such as information processing. These studies have all utilized a cycle ergometer (Mang et al., 2014; Roig et al., 2012; Tsukamoto, Suga, Takenaka, Tanaka, Takeuchi, Hamaoka, Isaka, & Hashimoto, 2016a; Tsukamoto, Suga, Takenaka, Tanaka, Takeuchi, Hamaoka, Isaka, Ogoh, et al., 2016b). Moreover, these studies using HIIT are similar in that they use longer work to rest ratios (3 minutes high intensity: 2 minutes low intensity). HIIT can also consist of brief exercise bouts (10-20 seconds), performed with maximal effort, followed by passive rest (Essen, Hagenfeldt, & Kaijser, 1977; Tabata et al., 1996). The effects of HIIT using shorter exercise and rest bouts on postural control, information processing, and motor skill acquisition have not yet been explored.

An investigation into other forms of HIIT may also be advantageous since it can incorporate a combination of resistance- and aerobic-based exercise, which have individually been well-established to positively impact cognitive function (Chang et al., 2012; Liu□Ambrose et al., 2008; Smith et al., 2010; Tomporowski, 2003). Researchers have also demonstrated that interventions incorporating both chronic aerobic- and resistance-based exercise yield significantly more improvement in cognitive functioning than either aerobic or resistance training alone (Colcombe & Kramer, 2003; de Asteasu, Martínez-Velilla, Zambom-Ferraresi, Casas-Herrero, & Izquierdo, 2017). However, the acute effects of a combined aerobic-resistance exercise bout have yet to be examined. Additionally, it has been reported that exercises requiring greater body awareness and more cognitive processes may have greater impacts on cognitive abilities (Gothe, Pontifex, Hillman, & McAuley, 2013). Therefore, an investigation into exercises requiring more body responsiveness as part of a HIIT routine would add to the limited evidence on the exercise mode and its effects on cognition and motor function.

Purpose

Based on previous literature, exercise may be an effective tool similar to movement-based priming techniques to improve postural control and motor skill acquisition. However, to date, few studies have investigated the effects of acute exercise on these parameters. Therefore, one purpose of this study was to examine the effects of acute exercise on postural control and motor skill acquisition. A second purpose was to compare the effects of an aerobic exercise HIIT protocol to a combined aerobic-resistance exercise HIIT protocol on cognitive function and motor abilities.

Research Hypotheses

H_1: Acute HIIT will lead to improved postural control (i.e., less center of gravity sway) on the unilateral stance test and the tandem walk test compared to the control group. Based on previous work using whole-body vibration training, it is hypothesized that acute exercise will serve as a means to prime the motor system, thus improving postural control (Bogaerts, Verschueren, Delecluse, Claessens, & Boonen, 2007; Rees, Murphy, & Watsford, 2009).

H_2: Acute HIIT will lead to improved information processing via shorter reaction time through reductions in peripheral processing (i.e., motor time) similar to previous research using surface electromyography (Audiffren, Tomporowski, & Zagrodnik, 2008, 2009; Beyer et al., 2017; Chang, Etnier, & Barella, 2009; Davranche et al., 2005; Davranche et al., 2006; Lambourne & Tomporowski, 2010; Tomporowski, 2003).

H_3: Acute HIIT will improve motor skill acquisition (i.e., lower total performance error) compared to the control group. This hypothesis is based on previous work suggesting that acute exercise improves motor skill acquisition (Mang et al., 2014; Statton et al., 2015).

H_4: Acute HIIT will lead to significantly fewer errors and faster reaction times on the executive function task compared to the control group similar to previous findings showing that acute cycling significantly improves executive function (Tsukamoto, Suga, Takenaka, Tanaka, Takeuchi, Hamaoka, Isaka, & Hashimoto, 2016a; Tsukamoto, Suga, Takenaka, Tanaka, Takeuchi, Hamaoka, Isaka, Ogoh, et al., 2016b).

Limitations

- Cognitive tests were performed in a specified order in which a temporal effect may have been present.
- The sample consisted of mainly young, healthy adults.
- The effects of acute exercise on both motor and cognitive tasks were assessed in a controlled laboratory environment.

Assumptions

- Participants avoided high-intensity exercise at least 24 hours prior to their visit.
- Participants refrained from consuming caffeine at least four hours prior to their visit.
- Participants would have informed the PI of any ailment that may have impaired their performance.
- Participants fully understood the testing instructions and performed all tasks to the best of their abilities.
- The integrated software maintained a one-to-one timing ratio during data acquisition.

Significance

- The findings add to the limited research investigating the effects of acute exercise on postural control and motor skill acquisition.
- This study used a novel exercise protocol that might be more convenient and appropriate for rehabilitative settings.

- The findings from this study are some of the first to observe effects of acute exercise on central processing using surface electromyography.

CHAPTER 2: LITERATURE REVIEW

Overview

The notion of exercise as a form of medicine is not novel; great thinkers have endorsed the concept since the time of Hippocrates (460-370 B.C.) and Galen (129-210 A.D.) (Berryman, 2010). Even before modern science enabled a more complete understanding of the benefits of exercise, it was referred to as a "blessed medicine" (Méndez, 1960). And as knowledge about the physiological and psychological effects of exercise have evolved over time, physicians and scientists have begun working collaboratively to bring scientific credibility to the therapeutic significance of exercise (Berryman, 2010; Johnson, 1960). Based on this work, the physiologic and cognitive benefits associated with acute and chronic exercise have now been well established (Garber et al., 2011; Hillman, Erickson, & Kramer, 2008). However, the effects of exercise on motor control and motor learning have received less attention. The proposed research study will examine the effects of acute exercise on cognitive function, motor control, and motor learning in healthy young adults. The following sections will briefly review past and present theories of motor control, postural control, information processing, motor skill acquisition, executive functioning, and how acute exercise is known to impact both motor control and cognitive function.

Motor Control

Motor control is the ability of the central nervous system (CNS) to use current and previous inputs to coordinate effective movement. Crucial to the concept of motor control is the ability of the CNS to integrate information and communicate with the peripheral nervous system (PNS) (Kandel, Schwartz, Jessell, Siegelbaum, & Hudspeth, 2000). To better understand the way in which the human body coordinates movement, several theories were developed and have evolved over time to help explain control of movement via central and peripheral pathways.

Closed-loop Theory

Jack Adams (1971) developed the closed-loop theory based on the idea that a closed-loop system can self-regulate using feedback to detect an error in reference to a predetermined goal (Figure 1) (Schmidt & Lee, 2011). According to this theory of motor control, movement is produced centrally and then is compared with sensory input from the actual movement performed. This feedback ultimately leads to modification of motor output to correct system stability (Horak, 1990). Therefore, according to the closed-loop theory, both cognitive and perceptual constructs are needed to initiate and properly control movement (Adams, 1971). Although this theory was once thought to explain motor control, other models have been found to more accurately explain motor control, and the closed-loop theory has little remaining impact on the field (Schmidt & Lee, 2011).

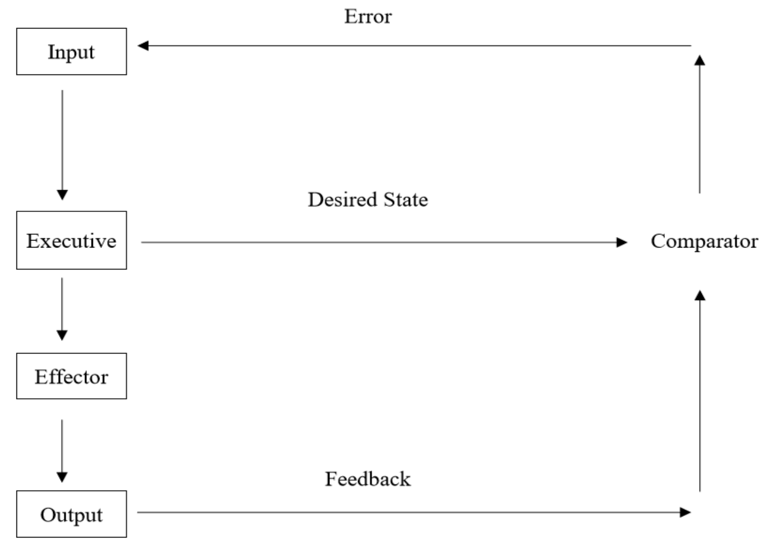

Figure 1. Closed-loop Control Model

Reflex Model of Motor Control

A second model developed to explain human movement is the reflex model, which has its early roots in the work of Sir Charles Sherrington (Horak, 1990; Sherrington, 1910). According to this model, reflexes are the basis of all movement and thus compounded reflexes are what ultimately comprise motor control (Figure 2) (Easton, 1972; Horak, 1990). Reflexes can certainly account for very fast movement since they do not rely on perceptual processing (Dewhurst, 1967). This theory of motor control is a 'peripheralist' view in that it asserts that motor control originates only from the peripheral components of the nervous system (Horak, 1990). One major assumption of the reflex model is that sensory input is required for normal motor output (Horak, 1990). This assertion represents a major limitation of the reflex model since empirical studies have demonstrated that movement is possible even with no sensory input (Brown, 1914). Additionally, the model cannot adequately explain goal-directed and anticipatory actions, which are generated in the CNS. The shortfalls of the reflex model thus highlight the need for models capable of explaining both mechanisms of feedback and feedforward control (Horak, 1990).

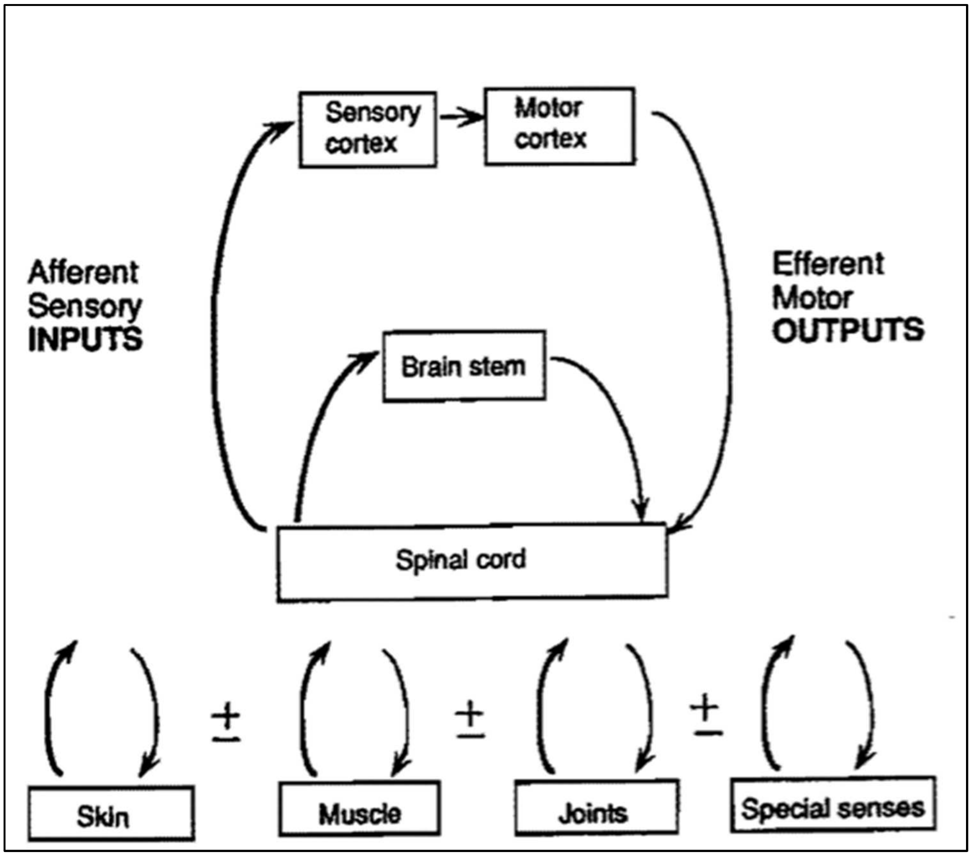

Figure 2. Reflex Model of Motor Control. (Adapted from (F. Horak, 1990))

Open-loop Theory

In contrast to the closed-loop theory, the open-loop theory does not utilize concepts of feedback or error-detection mechanisms (Schmidt & Lee, 2011). An open-loop process includes input, instructions, and output (Figure 3). Open-loop theories are favored when researching motor control since rapid and ballistic movements are typically completed before any sensory input can correct or regulate them (Horak, 1990). When movements occur rapidly, prior to any feedback, the movement relies on a function known as feedforward control. Feedforward control of movement results in an anticipatory action based on previously learned and programmed responses within the brain (Horak, 1990). Feedforward control is a powerful explanatory concept in motor control since it explains how the motor system can send signals to various spinal levels to prepare for movement or ready motor unit pools for expected signals (called spinal tuning) (Schmidt & Lee, 2011). The finetuning and correcting of movement is accomplished by stored prior experiences, the initial body position when the movement was learned, cognitive information, and expectations of body-environment interaction (Horak, 1990).

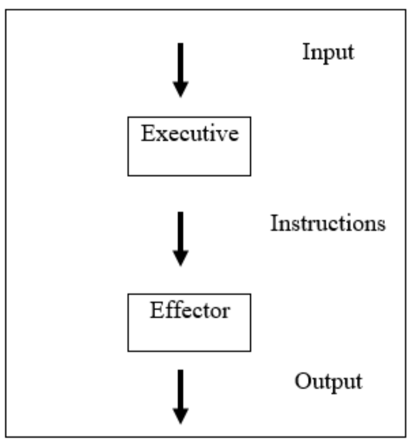

Figure 3. Elements of Open Loop Control

Schema Theory

Due to the limitations of Adams' (1971) closed-loop theory described previously, Schmidt (1975b) developed the schema theory, which specifically addresses the lack of an open-loop control process within the original closed-loop theory. The schema theory borrowed heavily from Adams by retaining effective components of the closed-loop theory (i.e., subjective reinforcement and concern for slow movements) and replacing its defective components. Specifically, the schema theory asserts that there are two types of memory: (1) recall memory (which produces movement) and (2) recognition memory (which evaluates that movement) (Schmidt & Lee, 2011). These two forms of memory are formed via existing movement parameters, sensory feedback, and the initial conditions in which the movement was made (Adams, 1987). The strength of this theory is that it seems to effectively explain rapid movements by proposing that they are carried out by recall memory and require minimal feedback from the PNS (Schmidt, 1975).

Hierarchical Control Model

The Hierarchical Control Model, which asserts that movement is controlled in a top-down fashion, was first proposed by Sir Huglings Jackson (Walshe, 1961). This theory (Figure 4) is based on the idea that a centrally-organized structure controls the majority of movement but is also highly responsive to sensory input as an additional contributor to motor control (Schmidt & Lee, 2011). It is hypothesized that higher-level processes are involved in decision making about movement, and these decisions are then carried out by lower-level processes. This model of motor control may be viewed as a high order open-loop system with closed-loop systems operating underneath. It thus provides a plausible explanation for both highly automatic (reflex) movements at the low level of the hierarchy and complex, intentional, movements at the high level of the hierarchy (Philips & Porter, 1977). As part of this theory, researchers have hypothesized that movement goals are developed at upper levels and are then transmitted to lower levels, which are responsible for the coordination, structuring, and ultimately the performance of the movement (Greene, 1972). Once a movement is practiced, it can be pre-programmed and then executed more rapidly when it is needed in the future (Kawato, Furukawa, & Suzuki, 1987). As an example, these pre-programmed patterns of movement are important in explaining postural control, as it encompasses a whole variety of anticipatory movements essential to the subsequent performance of voluntary movement (Belen'kiĭ, Gurfinkel, & Pal'tsev, 1967; Mathiowetz & Haugen, 1994). In postural control, high order processes are responsible for forming an internal representation of body posture while low order processes regulate kinematics and force in order to control the movement (Massion, Alexandrov, & Frolov, 2004). The hierarchical theory finds its strength in its ability to account for both centrally- and peripherally-driven responses, along with its recognition of the importance of both high-order processes (i.e., information processing and executive functions) and low-order processes (i.e., reflexes and peripheral motor response) to overall motor control.

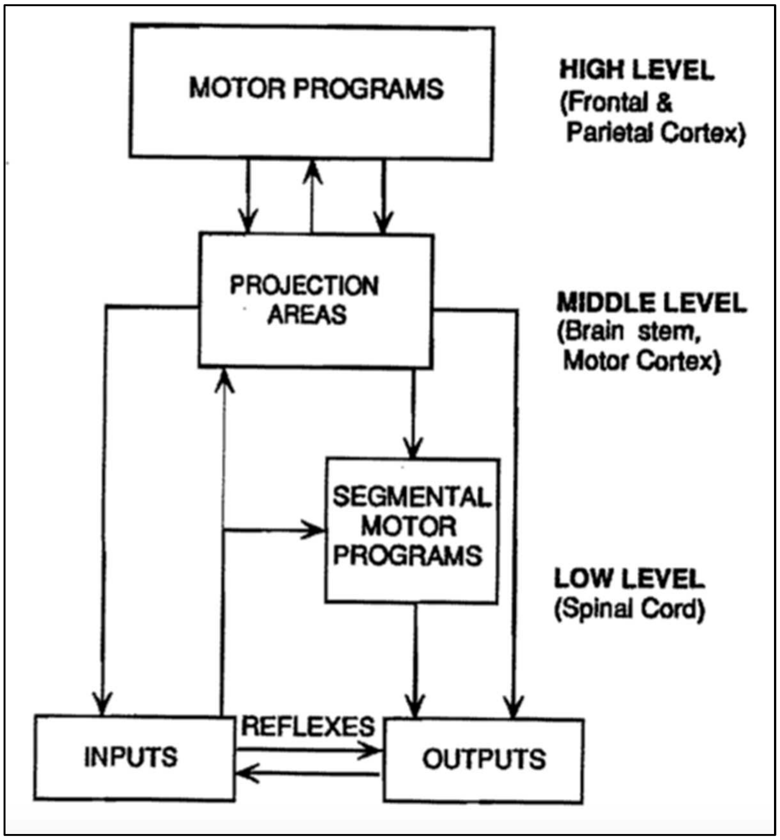

Figure 4. Hierarchical Model of Motor Control (Adapted from (Horak, 1990))

Postural Control

Postural control requires both sensory input from the PNS and integration of this information via higher-order processes (Geurts, Mulder, Nienhuis, Mars, & Rijken, 1992; Maylor & Wing, 1996; Teasdale, Bard, LaRue, & Fleury, 1993). Sensory information essential for postural control is obtained from the vestibular, visual, and proprioceptive systems, and the integration of this information along with the configuration of postural control systems occurs centrally (Lepers, Bigard, Diard, Gouteyron, & Guezennec, 1997). Postural stability is critical to the performance of all activities of daily living (ADLs) (Kanekar & Aruin, 2014). Although it's clear that postural control plays a key role in maintaining balance, it does so via highly complex mechanisms which make it difficult to study with precision (since many individual postural adjustments may only account for a few degrees of sway) (Hayes, 1982; Horak, 1987). Measurement of postural control through sway (the horizontal movement of the center of gravity) is difficult because a person's center of gravity is not easily determined (Horak, 1987; Murray, Seireg, & Scholz, 1967). Moreover, researchers have highlighted that even drastic compensation methods to maintain balance might only appear as a small change in the center of gravity (Horak, 1987). Given this challenge, highly sensitive techniques to evaluate sway are necessary in order to accurately assess postural control. One common method of postural control measurement is a force plate. Force plates can measure the force exerted through a person's foot and ultimately the sway of their center of gravity. Adding to the challenge of precisely measuring postural control is the need to measure it under both static and dynamic conditions, given that its efficiency is greatly impacted by the complexity of simultaneous demands placed upon the motor control system (Hayes, 1982). Thus, measuring postural control under both conditions provides important information on a person's functional capabilities.

Information Processing

An important underlying assumption in the study of motor behavior and motor control is the fact that humans are processors of information (Schmidt & Lee, 2011). More specifically, humans receive information from sensory inputs, store that information, and ultimately process the information for various purposes (including physical movement.) Given the importance of information processing in the production of movement, understanding factors that affect the efficiency of information processing has important implications for designing interventions to enhance the efficiency of motor control.

One way researchers have indirectly studied information processing is by studying reaction time (RT). F.C. Donders was the first to measure the time it took an individual to complete a simple motor task and to isolate the time required for the component operations involved in the task (Donders, 1969). He developed the subtractive method for this purpose, in which he asks the subject to complete two tasks which are identical except for a single mental operation thought to be essential to one task and absent in the other. Following completion of the tasks, he subtracts the time required to complete the tasks and arrives at an estimate of the time required for a specific component mental operation. Still today, Donder's method serves as the foundation for how human information processing is analyzed (Schmidt & Lee, 2011). Building on the work of Donders, many researchers have proceeded to study information processing using a variety of different models (Kellogg, 2002; Sanders, 1980; Schweickert, 1993; Sternberg, 1969). Although each model is unique, they all share the same main components.

One prominent information processing model is detailed in Figure 5 (Schmidt & Lee, 2011). Broadly, this model can be broken down into three stages: (1) stimulus identification, (2) response selection, and (3) response programming.

Stimulus (Input)	→	Stimulus Identification	Response Selection	Response Programming	→	Movement (Output)
←			Reaction Time	→		

Figure 5. The Information Processing Model

The stimulus identification stage occurs immediately following the onset of a stimulus. This stage can be broken down further into two distinct phases: (1) stimulus detection, which involves the initial activation of nerves at the site of the stimulus and the transmission of the electrical signal to the CNS and (2) pattern recognition, which involves an array of both conscious and unconscious processing in the CNS that leads to activation of appropriate associative memory (Schmidt & Lee, 2011). Stimulus intensity (e.g., the brightness of a light stimulus) and the novelty of a task both impact the time required for this stage of processing.

The model proceeds to the second stage, response selection, once a stimulus input has been received and analyzed by the CNS. During this stage, an individual decides on the appropriate response to a particular stimulus. The time required for response selection is highly variable and is influenced by a variety of factors, including the number of possible responses to the stimulus. This relationship between the number of stimulus-response (S-R) pairings and RT has such a predictable relationship that the researchers who first observed it developed Hick's Law, which highlights the need to account for the number of S-R pairings when studying RT (Hick, 1952; Hyman, 1953). Hick's Law states that for every doubling of S-R pairs, RT increases by 150 ms (Schmidt & Lee, 2011).

Another factor that impacts response selection time is S-R compatibility. Simon (1990) used this term to describe the "naturalness" of a response to a stimulus. For example, an individual will have a shorter RT if they are told to respond with their right hand when they see a right facing arrow as opposed to if they are told to respond with their left hand when they see a right facing arrow. When the S-R is mixed (e.g., right-facing arrow with a left-handed response), RT is likely to increase, an effect referred to as the Simon Effect (Simon & Rudell, 1967). This effect is noticeably absent when the stimulus is irrelevant to the appropriate response selection (Schmidt & Lee, 2011).

The final stage of the information processing model is response programming. After sensory inputs have been detected, identified, and an appropriate response has been selected, the necessary component motor actions must take place to achieve the desired outcome (Schmidt & Lee, 2011). As with the previous stages, the time required for this stage is variable and dependent on a number of components. Henry and Rogers (1960) were some of the earliest researchers to conclude that as movement complexity increases so too does total RT. Specific properties of movement complexity that seem to impact RT are: (1) the number of moving parts, (2) the requirement of movement accuracy, and (3) the duration of the movement. As movement complexity increases, more neuromotor activities must be coordinated, requiring increased time for neurologic organization and ultimately resulting in a longer RT. The concept of neurologic organization is particularly important to the study of motor programming (Schmidt & Lee, 2011).

Fractioned Reaction Time

Although information processing time can only be indirectly measured via RT, the processing time of both the CNS and PNS can be more objectively measured through fractioned reaction time (FRT) (Figure 6). The concept of FRT was developed by Weiss (1965) and allows for more objective measurements of central processing time (premotor time (PMT)) and peripheral processing time (motor time (MT)). PMT is the time from stimulus display to the appearance of muscle action and MT is the duration of muscle activity through the completion of the behavioral action. More specifically, PMT reflects the early stages of information processing while MT represents the time of electro-mechanical transduction within the muscle fibers (Audiffren et al., 2008). Although FRT is a useful tool for assessing PMT and MT, few exercise-related studies have incorporated techniques capable of measuring FRT. Of the studies that have examined the effects of acute exercise on information processing, only three have used electromyography (EMG) to fractionate RT (Audiffren et al., 2008; Beyer, Sage, Staines, Middleton, & McIlroy, 2017; Davranche & Audiffren, 2004; Davranche et al., 2005). These studies found decreases in MT following acute exercise, but not in PMT, suggesting that exercise may have an influence on muscle activation but not arousal. Two of the studies did notice an interaction effect between signal intensity and exercise on PMT (Davranche et al., 2005; Davranche, Burle, Audiffren, & Hasbroucq, 2006). The authors stated that, although only a small effect was observed, exercise may affect sensory processes. Given the few studies which have specifically assessed the effects of exercise on the sensory processing stages, more research is certainly needed (Audiffren et al., 2008).

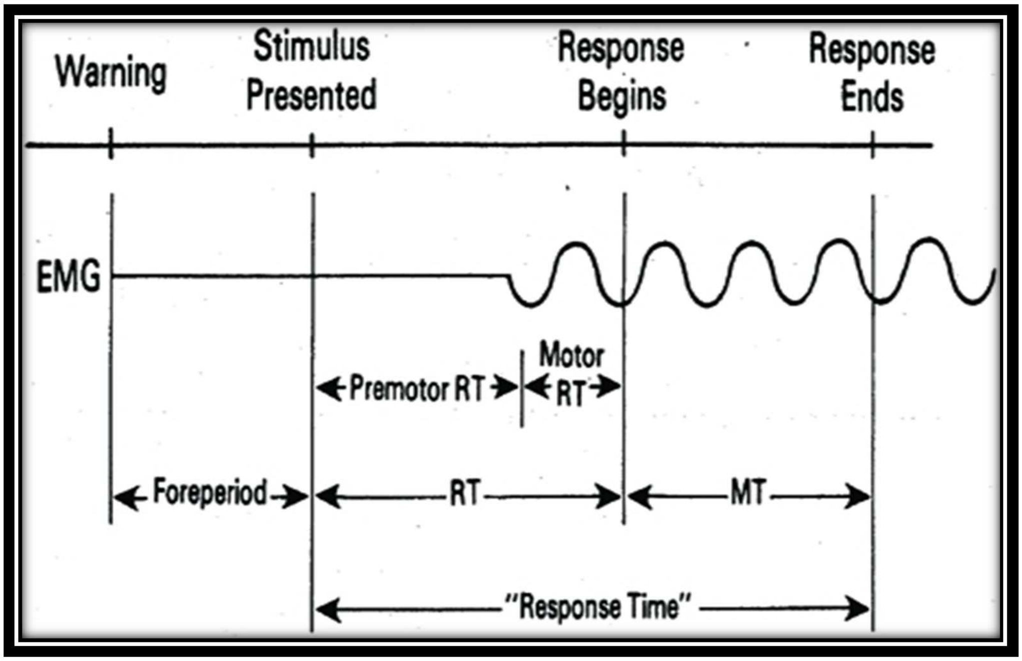

Figure 6. Example of Fractioned Reaction Time

Motor Skill Acquisition

Like information processing, understanding motor skill acquisition is essential to the study of motor behavior and motor control. The concept of motor skill acquisition was influenced by early information processing models along with many cognitive frameworks (Newell, 1991). The basic model states that whenever individuals perform a motor task, they receive feedback about the results of the task, which is referred to as knowledge of results (KR). As KR compounds, it builds upon previously stored memories about the task and thereby improves performance of the motor task. These stored memories (which collectively form a memory trace) can then be recalled to initiate a more specific and swift motor response in the future. The importance of KR and memory traces to motor skill acquisition highlights the importance of both the cognitive and perceptual functions of the motor control system (Adams, 1987).

Impulse-Variability Theory

The impulse-variability theory holds that impulse is a critical component of movement and that the variability of impulse is a major determinant of the variability of movement (Schmidt, Zelaznik, Hawkins, Frank, & Quinn Jr, 1979). The impulse-variability theory provides a powerful explanation of sources of error in movements which do not rely heavily on feedback (Schmidt, Sherwood, Zelaznik, & Leikind, 1985; Schmidt & Lee, 2011). Moreover, the impulse variability theory highlights that movements that are performed quickly usually sacrifice spatial accuracy and vice versa (Schmidt et al., 1985). Today this is commonly referred to as the speed-accuracy tradeoff. During motor skill acquisition, a person might reduce speed in order to improve accuracy. Once the skill is learned, the person may be able increase the speed at which the skill is performed while maintaining accuracy as well.

One test that is commonly used to measure motor skill acquisition is a force-control test. In this test, an individual is asked to reproduce a force-time curve presented on a screen with the aim of approximating the timing and magnitude of force reflected on the given curve as closely as possible (example is shown in figure 7). Total performance error is then calculated using the equation $E = \text{Sqrt}(\sum[X_i - T_i]/n)$ where X_i is actual performance, T_i is target performance, and n is total number. This test specifically assesses impulse—that is, the force applied over time and a critical determinant of what the limb will do when the attached muscles are activated (Schmidt & Lee, 2011). More simply stated, a motor program communicates to the muscles when to turn on and how much force needs to be generated. Therefore, a test such as the force-control test is an appropriate way to assess a motor program or the acquisition of a new motor program.

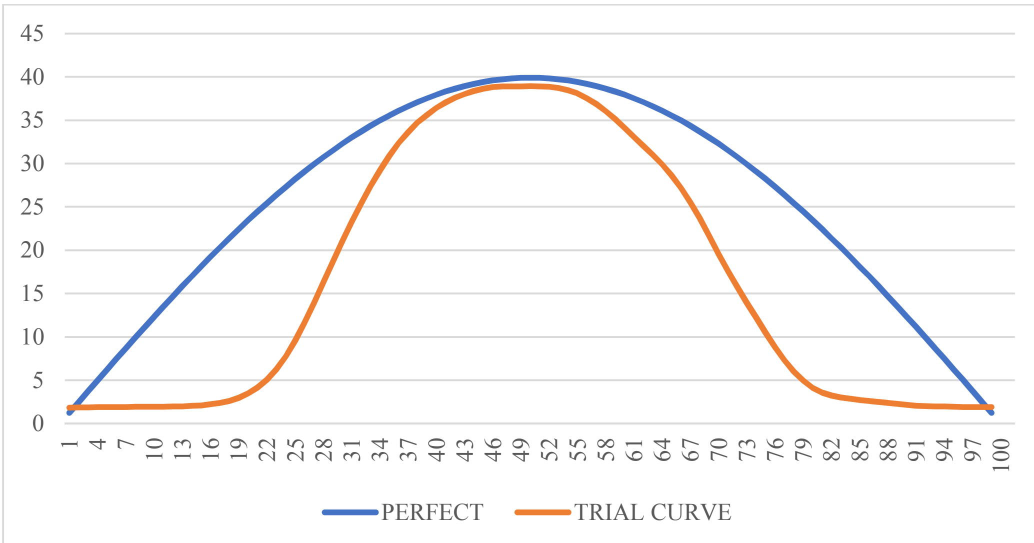

Figure 7. Example of Force Control Test

Executive Function

Executive function (EF) consists of higher mental processes involved in attentional control, planning, and inhibition. EFs originate in the frontal lobe, specifically the prefrontal and dorsolateral prefrontal cortex (Raz, 2000). While these processes are crucially important for a whole range of human behavior, they are also intricately involved in the utilization and modification of sensory information to produce behavior (Fuster, 1999; Yogev□Seligmann et al., 2008). Therefore, properly operational EFs are associated with a person's ability to walk efficiently, avoid falls, and perform a whole range of other motor control tasks (Van Iersel et al., 2006; Yogev□Seligmann et al., 2008). Moreover, according to the hierarchical model of motor control, higher-level decision-making often relies on EFs like planning and inhibition for necessary control and correction of movement. Improved efficiency of EFs, therefore, have important implications for optimizing motor control and motor behavior.

Acute Exercise and Cognition

The effect of a single bout of acute exercise on cognitive function has been well established. Acute aerobic exercise has been shown to improve attention, response speed and accuracy, short- and long-term memory, and other EFs such as problem-solving and goal-oriented action (Ludyga et al., 2016b; Roig, Nordbrandt, Geertsen, & Nielsen, 2013; Tomporowski, 2003). Current findings suggest that cognitive performance is enhanced immediately following very light, light, and light-moderate exercise while cognitive performance immediately following intense exercise is either unchanged or diminished. However, after some delay following acute exercise, researchers have reported an enhancement in domains such as inhibitory control, memory, and reaction time (Lambourne & Tomporowski, 2010). These findings support the relationship between physiologic responses to exercise and cognitive function (Chang et al., 2012). Findings from previous research also support domain-specific responses to exercise. For example, moderate-intensity exercise appears to benefit executive functions while high-intensity exercise has demonstrated greater effects on information processing (Chang, Chu, Chen, & Wang, 2011; Chang & Etnier, 2009b).

In addition to exercise intensity, exercise duration can moderate the effects of acute exercise on cognitive performance. Researchers have reported that exercise should be at least 20 minutes in length in order to elicit positive effects (Brisswalter, Collardeau, & René, 2002; Chang et al., 2012; Lambourne & Tomporowski, 2010). Shorter duration of exercise does not appear to elicit any significant changes in performance while prolonged exercise leads to fatigue, which negatively affects cognitive performance (Lambourne & Tomporowski, 2010). Understanding and accounting for this dose-response relationship are important for exercise prescription targeted at enhancing cognitive function (Chang et al., 2015).

Although the effect of exercise intensity and duration on cognitive function has received much attention, the effect of exercise mode has received less investigation. The majority of research has observed the effects of steady-state aerobic exercise either on a treadmill or cycle ergometer, while much less attention has been given to circuit training and resistance training protocols (Lambourne & Tomporowski, 2010). Studies that have observed the effects of acute resistance training have mainly reported positive but somewhat inconsistent impact on cognitive functioning (Brush, Olson, Ehmann, Osovsky, & Alderman, 2016; Chang & Etnier, 2009a; Chang et al., 2012; Chang, Tsai, Huang, Wang, & Chu, 2014; Coles & Tomporowski, 2008; Gates, Singh, Sachdev, & Valenzuela, 2013; Pontifex, Hillman, Fernhall, Thompson, & Valentini, 2009). However, upon close review of these studies, variation in exercise prescription, type of resistance training (e.g., machine vs. free weight vs. body weight), individual training status, and precise domain of cognitive function tested likely contribute to inconsistency in findings. Additionally, similar to aerobic exercise, there does appear to be a dose-response relationship between duration and intensity of resistance training and the observed impact on cognitive functioning. Chang et al., (Chang & Etnier, 2009b) found that high-intensity resistance exercise benefits processing speed while moderate-intensity exercise benefits executive functioning. Still, with so few studies examining the effects of acute resistance training on cognitive performance, additional research is required to draw more definitive conclusions (Chang et al., 2015).

Other modes of exercise such as high-intensity interval training (HIIT) have received even less attention in the literature and also require further investigation to understand their impact on cognitive function and motor control. HIIT involves intensive aerobic exercise followed by passive or active rest periods. These exercise to rest ratios typically are 2:1 or 1:1 consisting of generally 15 to 30 seconds, but up to 60 seconds, of exercise at a time (Boyne et al., 2013). Moreover, HIIT usually involves exercise above anaerobic threshold with passive rest of light exercise bouts interspersed (Gibala & McGee, 2008; Laursen & Jenkins, 2002; Weston, Wisløff, & Coombes, 2014). In healthy adults and clinical populations HIIT has been shown to improve maximal oxygen uptake, increase stroke volume, and increase pulmonary diffusion capacity over eight weeks (Hatle et al., 2014; Little et al., 2011).

With respect to its impact on cognitive performance, the few studies that have investigated HIIT have reported improved selective attention, decreased reaction time, improved response accuracy, and increased inhibitory control (Alves et al., 2014; Kao, Westfall, Soneson, Gurd, & Hillman, 2017; Tsukamoto, Suga, Takenaka, Tanaka, Takeuchi, Hamaoka, Isaka, & Hashimoto, 2016a; van Dongen, Kersten, Wagner, Morris, & Fernández, 2016). Research has not demonstrated an impact on short-term memory, but several researchers have hypothesized that a “ceiling effect” on performance may account for this (Lemmink & Visscher, 2005). Despite early findings suggesting that HIIT may benefit cognitive performance, further research is needed to fill in existing gaps in the literature. Of the previously mentioned studies on HIIT, four of the studies examined interval training on a cycle ergometer and one incorporated interval running on a treadmill. These studies also prescribed specific intensities based on either participants' maximum heart rate or VO_{2Peak}. Therefore, an investigation into other forms of HIIT with different exercise durations is warranted.

Acute Exercise and Motor Control

Compared to the literature on the impact of exercise on cognitive functions primarily facilitated by the prefrontal cortex, there is a true paucity of data about the effect of acute exercise on the motor cortex itself (Basso & Suzuki, 2017; Chang et al., 2012; Singh & Staines, 2015). Emerging evidence has shown that acute aerobic exercise can regulate motor cortex inhibition, enhance neuroplastic responses, and prime the motor areas for experience-dependent plasticity (McDonnell et al., 2013; Mooney et al., 2016; Singh, Neva, & Staines, 2014; Singh & Staines, 2015). Though these studies have demonstrated that acute exercise holds promise of benefit based on the physiology of the motor cortex, research is needed to understand how specific behavioral measures (e.g., gross motor function) related to motor performance and motor learning (e.g., motor skill acquisition) might be positively impacted by acute exercise.

Of the studies that have examined the effects of acute exercise on behavioral motor learning tasks, researchers have reported improved motor memory, motor skill retention, and motor learning (Mang et al., 2014; Mang, Snow, Wadden, Campbell, & Boyd, 2016; Perini, Bortoletto, Capogrosso, Fertonani, & Miniussi, 2016; Roig et al., 2012; Skriver et al., 2014; Statton et al., 2015). The majority of these studies have examined moderate-intensity, steady-state aerobic exercise or alternating bouts of higher and lower intensity exercise on a cycle ergometer. Some studies have also demonstrated that exercise improves components of motor control such as information processing, but could not make inferences about behavioral measures of gross motor function since no such assessments were included in the studies. This makes it difficult to determine if there is truly any relationship between improved information processing and enhanced motor control following acute exercise (Davranche & Audiffren, 2004; Davranche et al., 2005). Given these gaps in the literature, additional research examining how acute exercise (including HIIT and resistance training) affects actual behavioral measures of motor learning is warranted (Singh, Neva, & Staines, 2016; Taubert, Villringer, & Lehmann, 2015).

CHAPTER 3: METHODOLOGY

Participants

Study participants (N = 60) were young adults (27 males, 33 females), between 18 and 40 years of age. Participants were recruited via Wayne State University (WSU) Academica and WSU Blackboard Learning Communities (Kinesiology, Health, and Sport Studies, Physical Therapy, and Occupational Therapy). Fliers were also shared in classes within the Kinesiology, Health, and Sport Studies Department and posted in the Eugene Applebaum Building and WSU recreation centers (Matthaei Recreation Center and Mort Harris Recreation Center). Participants were required to complete two study visits, have no reported history of falls, be free of any mental diseases, and be healthy, which was defined as answering "no" to all questions on the Physical Activity Readiness Questionnaire (PAR-Q) (Chisholm, Collis, Kulak, Davenport, & Gruber, 1975). Participants were asked to refrain from high-intensity exercise in the 24 hours prior to testing and to avoid caffeine intake for at least 4 hours prior to testing. All testing sessions were scheduled at the same time of the day, and sessions for individual participants were scheduled at least 3 days apart. Students were free to choose whether to participate in this research study after receiving a detailed explanation of the purpose and possible risks and benefits associated with participation in the study. University Institutional Review Board approval was obtained prior to consenting any participants. All participants provided written consent in accordance with the guidelines from the Human Investigations Committee of the University. None of the participants had any prior knowledge of the research hypotheses and expected study outcomes.

Testing Protocol

Testing was accomplished in two sessions per participant (Figure 7), spaced over the course of one to two weeks. The first testing visit served to establish a baseline or pretest for each participant. Upon arrival, a member of the research team reviewed the informed consent with the participants and answered any questions about the study. Participants then completed the Physical Activity Readiness Questionnaire (PARQ). If the participants were physically able and agreed to participate in this study, they then participated in a one-hour baseline visit (Figure 8). After completing all motor and cognitive tasks, the Bruce Protocol was used to assess cardiovascular fitness (Pescatello, Arena, Riebe, & Thompson, 2014). The Bruce Protocol is an incremental treadmill test in which speed and incline are increased every 3 minutes until the participant indicates they can no longer continue. $VO2_{Peak}$ was assessed for each participant to serve as a control variable when analyzing reaction time, motor skill acquisition, executive function since cardiovascular fitness is known to be strongly associated with cognitive abilities (Hillman, Erickson, & Kramer, 2008). Following the baseline visit, participants were randomized to either the control group, aerobic only exercise group, or aerobic/resistance exercise group.

Visit 1
Informed Consent
Baseline Vitals – Age, Height, Weight, Resting Blood Pressure, and Heart Rate
Baseline Tests:
1. Postural Sway Test
2. Information Processing Test
3. Force Production Control Test
4. Executive Functioning Test
5. $VO2_{MAX}$ Testing

Randomized to either Control, HIIT-A, or HIIT-AR

Visit 2
Exercise or Rest Session
1. Postural Sway Test
2. Information Processing Test
3. Force Production Control Test
4. Executive Functioning Test

Figure 8: Flow and Order of Testing

Exercise Protocols

Participants in either of the exercise groups followed a 20-minute DVD-based routine of either high-intensity aerobic exercise (HIIT-A) (Figure 9) or high-intensity aerobic/resistance exercise (HIIT-AR) (Figure 10), depending on the group to which they were randomized. A certified strength and conditioning specialist created the DVD routines used by both groups. Specific exercises included on the DVDs are listed in Figures 9 and 10. Each exercise session included a 2.5-minute warm-up (consisting of three sets of jumping jacks), a 15-minute period of exercise (six sets of three exercises), and a 2.5-minute cool-down (three sets of jumping jacks). A set was defined as 20 seconds of exercise followed by 20 seconds of passive rest. Participants were asked to exert themselves to the maximal intensity they felt they could maintain for the duration of the DVD. Modified versions of each exercise were provided if participants needed to lessen the intensity and difficulty of an exercise. A trained research staff member supervised all exercise testing to ensure the safety of all participants. Following each exercise session, participants rested for ten minutes before completing the testing measures.

Figure 9. HIIT-A Protocol

20 minutes Total
- 20 seconds of exercise to 20 seconds of rest
- 6 sets of each exercise
- 1-minute rest between exercises

Warm-up – 2.5 minutes total
1. Jumping Jacks (3 sets)

Exercise Routine – 15 minutes total
2. Stationary High Knees (6 sets)
3. Burpees (6 sets)
4. Mountain Climbers (6 sets)

Cool Down – 2.5 minutes total
5. Jumping Jacks (3 sets)

Figure 10. HIIT-AR Protocol

20 minutes Total
- 20 seconds of exercise to 20 seconds of rest
- 6 rounds for each exercise
- 1-minute rest between exercises

Warm-up – 2.5 minutes total
1. Jumping Jacks (3 sets)

Exercise Routine – 15 minutes total
2. Squat to overhead press (6 sets)
3. Push-ups with DB rows (6 sets)
4. Single Arm DB Snatch [Alternating arms each 20 seconds] (6 sets)

Cool Down – 2.5 minutes total
5. Jumping Jacks (3 sets)

Control Condition

Participants randomized to the control group were brought into the lab to sit for 20 minutes while perusing exercise-related books and magazines. Participants were also allowed to sit quietly during the rest period if they desired. An inactive control was used based on similar research investigating the impact of acute exercise on cognitive function (Kao, 2017). Following the 20-minute rest, individuals were prepped for the battery of tests similar to participants in the exercise groups.

Baseline Vitals and VO2$_{Peak}$

This study concluded with 60 total participants with 19 randomized to the control group, 21 randomized to the HIIT-A group, and 20 randomized to the HIIT-AR group. Participant's height and weight were assessed during the baseline session. The participants were measured for height to the nearest centimeter and weight was measured to the nearest 0.5 kilograms (SECA, Creative Health Products, Plymouth, MI). Body mass index (BMI) was used to assess weight in relation to height. BMI was calculated by dividing body weight in kilograms by height in meters, squared (kg/m^2) (Gallagher et al., 2000). Mean ± SE for baseline characteristics of the three groups and total for all participants are detailed in Table 1.

Table 1. Baseline Vitals and $VO2_{Peak}$

	Control (n = 19)	HIIT-A (n = 21)	HIIT-AR (n = 20)	Full Sample (n = 60)	*p*
Gender	Males = 9 Females = 10	Males = 8 Females = 13	Males = 10 Females = 10	Males = 27 Females = 33	.733
Age (years)	22.6 ± 1.1	22.8 ± .07	24.0 ± 1.3	23.1 ± 0.6	.628
Height (cm)	167.1 ± 1.5	170.7 ± 2.0	169.7 ± 2.0	169.2 ± 1.1	.394
Weight (kg)	78.0 ± 5.9	69.9 ± 3.1	74.5 ± 3.1	74.1 ± 2.4	.352
BMI (kg/m^2)	28.1 ± 2.3	23.8 ± 0.7	25.8 ± 0.9	25.8 ± 0.8	.098
Resting HR (bpm)	80.9 ± 9.9	75.6 ± 11.3	75.4 ± 13.4	77.1 ± 11.7	.286
Blood Pressure (Systolic/Diastolic) (mmHg)	118.8/76.6	117.7/78.7	118.5/77.1	118.3/77.5	.950
$VO2_{Peak}$ (mL/kg/min)	35.9 ± 2.8	46.1 ± 1.9	40.5 ± 2.1	41.0 ± 1.4	.009*

*$p < 0.01$

Following the analyses, there were no differences between the groups at baseline for sex, age, height, weight, and BMI. There was, however, a significant difference in VO_{2Peak}. The HIIT-A group (M = 46.1, SE = 1.9) had a significantly higher measure of VO_{2Peak} compared to the control group (M = 35.9, SE = 2.8).

Exercise and Testing Characteristics

During exercise, heart rate (HR) and ratings of perceived exertion (RPE) were recorded after each set of exercise and were averaged to calculate exercise HR and RPE. Additionally, HR was recorded for each participant prior to the initiation of the testing protocol. Results can be found in Table 2. Between the exercise groups, there was a significant difference in mean HR, with the HIIT-A group (M = 168.1, SE = 2.0) exercising at a significantly higher HR than the HIIT-AR (M = 156.6, SE = 3.1). On average, the

HIIT-A group exercised around 85% age-predicted maximum HR while the HIIT-AR group exercised on average around 80% age-predicted maximum HR (Karvonen, 1957). There was no difference between the groups for ratings of perceived exertion during the exercise bout. Following exercise and a 10-minute recovery period, the exercise groups had a significantly higher HR at the start of testing compared to the control group ($p < .001$). There was no significant difference between the groups on RPE.

Table 2. Exercise and Testing Characteristics

	Control (n = 19)	HIIT-A (n = 21)	HIIT-AR (n = 20)	Full Sample (n = 60)	*p*
Exercise HR Heart Rate (bpm)	N/A	168.1 ± 2.0	156.6 ± 3.1	N/A	.003*
% Max Heart Rate	N/A	85.2 ± 1.2	80.0 ± 1.5	N/A	.007*
RPE	N/A	16.5 ± 2.6	13.9 ± 0.5	N/A	.352
Pre-Testing HR (bpm)	77.3 ± 10.3	94.1 ± 10.2	95.4 ± 9.5	90.3 ± 12.5	.001*
Pre-Testing RPE	6.0 ± 0.0	6.2 ± .9	6.0 ± 0.0	6.1 ± .6	.603

*$p < 0.01$

CHAPTER 4: POSTURAL CONTROL

Task and Procedure

Postural control under static and dynamic conditions was measured during both study visits using a Balance Master® (Neurocom Smart Systems®).

Unilateral Stance Test

The first test administered was the unilateral stance test (UST). Participants stood on one leg and were asked to stand as still as possible for 10 seconds. Participants stood with their hands on their hips and held the non-standing leg in the air at a 90-degree angle per test instructions (Figure 11). Testing consisted of 6 trials (3 per leg) which were alternated between each leg. Following the 6 trials with eyes open, 6 additional trials were completed following the same protocol but with eyes closed. Center of gravity (COG) sway (degrees per second) was measured and recorded for each trial. Trials were averaged to provide a mean score for postural sway under each condition (eyes open and eyes closed).

Figure 11. Example of the Unilateral Stance Test

Tandem Walk Test

Following the UST, participants performed the tandem walk test (TWT). Participants took 5 steps in a straight line, stepping one foot directly in front of the other, and then were told to hold as still as possible for 10 seconds until instructed to relax (Figure 12). During the assessment, stride length, stride speed, and end sway were measured. The UST and TWT provided information on postural sway in degrees per second under static and dynamic conditions.

Figure 12. Example of the Tandem Walk Test

Statistical Analyses

For the static balance assessments, dependent variables of interest were mean COG sway (degrees per second) with eyes open and eyes closed. For the dynamic balance assessment, dependent variables of interest were stride speed and mean COG sway for the tandem walk. Separate mixed 3 (Groups: control group, aerobic group, aerobic/resistance group) x 2 (Tests: pre and posttest) analyses of variance (ANOVA) were used to analyze each dependent variable. Post-hoc analyses were performed using the Bonferroni test when appropriate to determine differences between groups (control, aerobic, and aerobic and resistance). Chi square test of independence was also used to analyze change (increase or decrease) in mean COG sway (pre to post) to examine any associations between group allocation and change. Statistical analyses were performed using SPSS (IBM SPSS Statistics, Version 25). Statistical significance was set at $p < .05$.

Results

Prior to conducting analyses, postural sway data was screened for outliers and normality. All scores for the UST and TWT were normally distributed for all groups as assessed by Shapiro-Wilk's test ($p > 0.05$) and visual inspection of the data. Levene's test of homogeneity of variance was also non-significant ($p > 0.05$). Postural sway measurements for the UST (Table 3) and TWT (Table 4) are presented as means ± standard error.

Table 3. Unilateral Stance Test Postural Sway Results

	Control (n=19)			HIIT-A (n=21)			HIIT-AR (n=20)		
	Pre	Post	*d*	Pre	Post	*d*	Pre	Post	*d*
Eyes Open	.951 ± .10	1.05 ± .17	.23	.766 ± .045	.787 ± .05	.10	.837 ± .05	.865 ± .09	.12
Eyes Closed	2.77 ± .20	2.54 ± .21	-.26	2.21 ± .15	2.22 ± .15	.01	2.34 ± .18	2.33 ± .16	.01

Note: All values represent degrees per second
Cohen's d is post-pre

Table 4. Walking Speed and End Sway for the Tandem Walk Test

	Control (n=19)			HIIT-A (n=21)			HIIT-AR (n=20)		
	Pre	Post	*d*	Pre	Post	*d*	Pre	Post	*d*
Speed	28.97 ± 2.52	33.63 ± 2.40	.42	32.68 ± 2.09	37.85 ± 2.51	.53	29.03 ± 1.87	34.39 ± 2.38	.64
End Sway	4.05 ± .37	3.69 ± .39	-.22	3.71 ± .34	3.61 ± .40	-.07	3.93 ± .34	3.45 ± .30	-.31

Note: Walking speed values represent meters per second
End sway values represent degrees per second
Cohen's d is post-pre

Baseline Results

At baseline, there was no significant differences between groups for eyes open balance ($F_{(2, 58)}$ = 1.810, p = .173, partial η^2 = .059) or eyes closed balance ($F_{(2, 58)}$ = 2.847 p = .066, partial η^2 = .089) on the UST. Additionally, no significant differences were observed between groups for speed ($F_{(2, 57)}$ = .984, p = .380, partial η^2 = .033) and end sway ($F_{(2, 57)}$ = .235, p = .791, partial η^2 = .008) on the TWT.

Posttest Results

Following the second visit, there was no interaction between group and time (pre and posttest) for single leg balance with eyes open ($F_{(2, 57)}$ = .593, p = .556, partial η^2 = .020) or eyes closed ($F_{(2, 57)}$ = 1.534, p = .224, partial η^2 = .051). Additionally, for the TWT, there was no significant interaction between group and time for speed ($F_{(2, 56)}$ = .088, p = .916, partial η^2 = .003) or end sway ($F_{(2, 56)}$ = .382, p = .684, partial η^2 = .013).

A chi square test of independence was conducted between groups to examine change (increase or decrease) in sway for the UST and TWT. All expected cell frequencies were greater than five. There was no association between group and change in sway for single leg balance with eyes open ($\chi^2(2)$ = 6.592, p = .159) and eyes closed ($\chi^2(2)$ = 2.753, p = .252). There was no association between group and change in speed ($\chi^2(2)$ = 1.107, p = .575) and change in sway ($\chi^2(2)$ = 1.295, p = .523) for the TWT.

Summary

The findings from this study show that acute HIIT exercise does not affect mean COG sway during static and dynamic tests of postural control. Further investigation into the data to look at trends (changes from pre to post) also demonstrated that exercise exhibited no effect on sway when compared to the control group. If either positive or negative effects as a result of exercise were present, it appears that a passive 10-minute cool down negates any observable effects on postural control measured by COG sway. Moreover, the apparatus used to measure postural control in this study might be more appropriate for measuring changes following chronic exercise training rather than immediate effects following acute exercise. To date, the research on exercise and postural control in young adults is quite limited. Similar investigations on acute HIIT and postural control are needed to confirm the findings from this present study. Moreover, additional research is needed to investigate other modes of exercise as well as different testing measures of postural control within this population.

CHAPTER 5: INFORMATION PROCESSING

Task and Procedure

Information processing was measured via a reaction time assessment on a desktop computer (Dell, Windows XP). Reaction time was measured using E-Prime 2.0 software (Psychology Software Tools, Pittsburgh, PA) and all responses were made on a Serial Response Box (SRB 200A, Psychology Software Tools). The software and response box were integrated with a MP100 data acquisition and analysis system with Acqknowledge software (BIOPAC Systems, Inc., Goleta, CA) allowing for measurement of surface electromyography (sEMG) during the task. This method of data measurement allows observation of both central and peripheral processes contributing to reaction time and has been employed in similar research studies previously (Davranche & Audiffren, 2004; Davranche et al., 2005). To measure sEMG, small, pre-gelled, cloth-based electrodes (EL504, BIOPAC Systems) were placed on the abductor pollicis brevis, which was used by all participants to respond to the stimulus. Concurrent feedback was provided prior to testing to make sure participants could maintain minimal muscle activity until a response was initiated.

For this test, participants sat at a computer with the response box positioned on a small table next to them so they could comfortably press the response key. The testing layout is pictured in Figure 13. Participants were asked to respond as quickly as possible to a stimulus by pressing the key on a response box. An example of one trial can be seen in Figure 14. Participants first saw a red circle lasting 1000 ms, indicating the beginning of the trial. Then they saw a yellow circle lasting between 1000 and 4000 ms as the foreperiod.

Finally, they saw a green circle to which they were asked to respond as quickly as possible. The green circle remained on the screen until the participant pressed the response key and completed the trial. After the response was made, RT was displayed to provide feedback for each trial. 1000 ms of a white screen appeared between each individual trial. All participants completed 2 blocks (16 trials total) in which the foreperiod varied from 1000-4000ms in a random order with a block average of 2500ms and 1 block (10 trials) in which the foreperiod was 2500ms for each trial. Each block started with instructions displayed on the computer screen and participants pressed the response key when they were ready to begin the block.

Figure 13. Testing Layout for the Information Processing Task

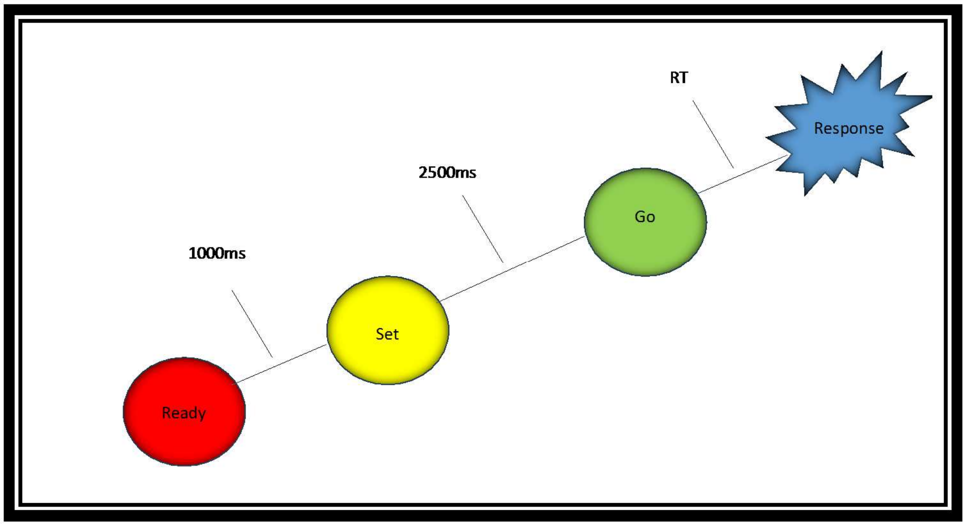

Figure 14. Example Sequence for an Information Processing Trial

Data Processing

Reaction times were averaged across each block to determine a mean reaction time (mRT), mean premotor time (mPMT), and mean motor time (mMT) for the irregular and regular foreperiod blocks. mRT was the average total time from the onset of the stimulus to the physical response. mRT was further fractioned into mPMT (central processing), which is the total time from the onset of the stimulus to the start of muscular activity, and mMT (peripheral processing), which is the total time from the onset of muscular activity to the physical response (Figure 15). RTs greater than 500ms were discarded and were presumed to be due to lack of task attentiveness and MTs less than 20ms were also excluded as they were likely due to equipment malfunction or random experimental error.

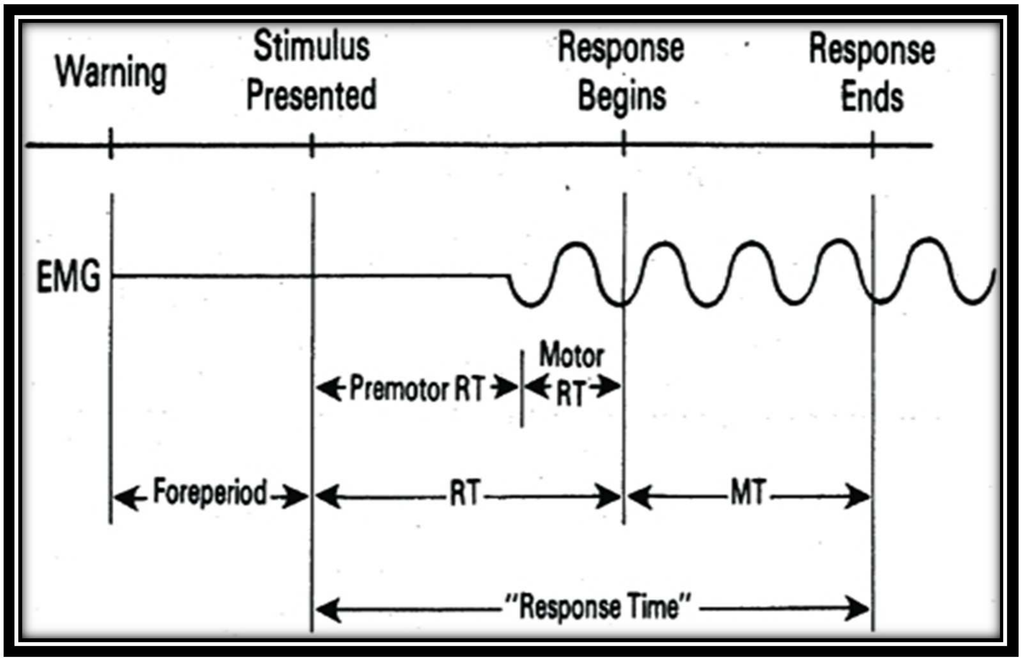

Figure 15. Example of Fractioned Reaction Time

Statistical Analysis

For both conditions (irregular and regular foreperiods), mRT, mPMT, and mMT were measured for each participant and analyzed using separate mixed 3 (control group, HIIT-A, HIIT-AR group) x 2 (pre and posttest scores) analyses of covariance (ANCOVA) controlling for cardiovascular fitness levels. Post-hoc analyses were performed using the Bonferroni test when appropriate to determine differences between groups (control, HIIT-A, and HIIT-AR). Statistical analyses were performed using SPSS (IBM SPSS Statistics, Version 25). Statistical significance was set at $p<0.05$.

Results

Prior to conducting analyses, data was screened for outliers and normality. Three data points were found to be greater than three standard deviations from the mean and were excluded from the analyses. Reaction time was normally distributed for all groups for each block, as assessed by Shapiro-Wilk's test ($p > 0.05$) and visual inspection of the data. Levene's test of homogeneity of variance for both conditions (irregular and regular foreperiods) was non-significant ($p > 0.05$). Reaction time values (mean ± standard error) for each condition and group are listed in Tables 5 and 6.

Table 5. Mean Reaction Times for Regular Foreperiod Trials

	Control (n=19)			HIIT-A (n=20)			HIIT-AR (n=18)		
	Pre	Post	*d*	Pre	Post	*d*	Pre	Post	*d*
Reaction Time	213.3 ± 4.1	220.6 ± 8.9	.41	232.3 ± 6.5	208.7 ± 7.3	-0.79	219.3 ± 5.3	204.9 ± 5.9	-0.61
Premotor Time	163.8 ± 3.4	161.0 ± 4.7	-0.19	169.5 ± 4.3	162.4 ± 5.4	-0.36	162.7 ± 4.1	159.0 ± 4.9	-0.20
Motor Time	50.5 ± 3.5	59.0 ± 5.0	0.55	63.7 ± 3.7	48.7 ± 3.6	-0.87	65.8 ± 7.8	47.2 ± 3.2	-0.54

Note: All values are presented in milliseconds (mean ± se)
Cohen's d post-pre

Table 6. Mean Reaction Times for Irregular Foreperiod trials

	Control (n=19)			HIIT-A (n=20)			HIIT-AR (n=18)		
	Pre	Post	*d*	Pre	Post	*d*	Pre	Post	*d*
Reaction Time	239.2 ± 4.4	248.1 ± 8.1	0.46	260.8 ± 6.9	219.8 ± 6.5*	-1.31	254.0 ± 6.2	217.2 ± 5.8*	-1.33
Premotor Time	184.7 ± 4.3	189.7 ± 5.7	0.27	194.1 ± 5.4	172.1 ± 4.6*	-0.89	196.0 ± 4.9	171.3 ± 4.8*	-1.14
Motor Time	55.2 ± 3.3	61.3 ± 4.3	0.43	65.6 ± 3.7	49.0 ± 4.3	-0.97	58.0 ± 4.3	47.1 ± 4.5	-0.57

Note: All values are presented in milliseconds (mean ± se)
Cohen's d is post-pre
**Significantly different from control (p < 0.05)*

Regular Foreperiod Trials

At baseline, when controlling for cardiovascular fitness, the control group (M = 213.3, SE = 4.1) was significantly faster than the HIIT-A group (M = 232.3, SE = 6.5) ($F_{(2, 53)} = 4.864$, $p = .011$, partial $\eta^2 = .148$). No differences were observed between any of the groups for PMT ($F_{(2, 53)} = 1.389$, $p = .258$, partial $\eta^2 = .047$) and MT ($F_{(2, 53)} = 2.646$, $p = .080$, partial $\eta^2 = .086$).

Following the intervention, when controlling for cardiovascular fitness, the interaction between group and time (pre and posttest) for mRT ($F_{(2, 51)}$ = 1.345, *p* = .270, partial η^2 = .050) and mMT ($F_{(2, 51)}$ = .363, *p* = .697, partial η^2 = .014) was not significant. There was a significant interaction between group and time for mPMT, $F_{(2, 51)}$ = 4.194, *p* = .021, partial η^2 = .141. This significant interaction was likely due to a simple main effect of time (pre to post) ($F_{(1, 51)}$ = 4.718, *p* = .035, partial η^2 = .085) and not group allocation.

Irregular Foreperiod Trials

Similar to the regular foreperiods, at baseline, the control group (M = 239.2, SE = 4.4) was significantly faster than the HIIT-A group (M = 260.8, SE = 6.9) ($F_{(2, 53)}$ = 5.849, *p* = .005, partial η^2 = .173). No differences were observed between any of the groups for PMT ($F_{(2, 53)}$ = 2.849, *p* = .066, partial η^2 = .092) and MT ($F_{(2, 53)}$ = 2.458, *p* = .095, partial η^2 = .081).

Following the intervention, when controlling for cardiovascular fitness, the interaction between group and time for mRT ($F_{(2, 51)}$ = 4.543, *p* = .015, partial η^2 = .151) and mPMT ($F_{(2, 51)}$ = 3.219, *p* = .048, partial η^2 = .112) (Figure 16) was significant. There was no significant interaction for mMT ($F_{(2, 51)}$ = 1.014, *p* = .370, partial η^2 = .038). For mRT, there was a significant simple main effect of group, $F_{(2, 53)}$ = 7.271, *p* = .002, partial η^2 = .215. Post hoc analyses revealed that the HIIT-A group (M = 219.8, SE = 6.5) and the HIIT-AR group (M = 217.2, SE = 5.8) had significantly faster mRTs than the control group (M = 248.1, SE = 8.1). The HIIT-A and HIIT-AR groups were not significantly different (*p* > .999). For mPMT, there was also a significant simple main effect of group ($F_{(2, 53)}$ = 4.275, *p* = .019, partial η^2 = .139). Post hoc analyses revealed the HIIT-A (M = 172.1, SE

= 4.6) and HIIT-AR exercise groups (M = 171.3, SE = 4.8) had significantly faster mPMTs than the control group (M = 189.7, SE = 5.7). The exercise groups were not significantly different from each other for mPMT (*p* > .999).

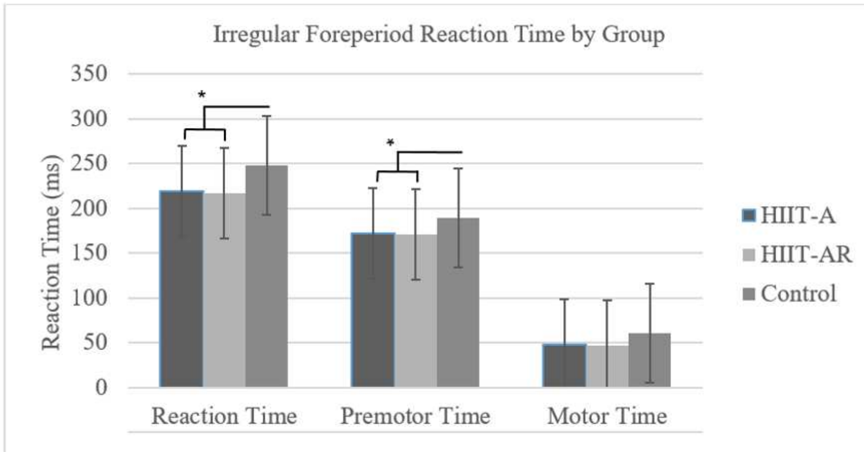

Figure 16. Reaction, Premotor, and Motor Time for Irregular Foreperiod Trials

Summary

This study demonstrated that acute HIIT-A and acute HIIT-AR can significantly improve reaction time in healthy adults. These results support the hypothesis that acute HIIT improves information processing speed in healthy young adults. Moreover, the reduced reaction time appeared to be a result of a reduction in PMT (central processing) rather than a significant change in MT (peripheral processing). This is contrary to the hypothesis that acute HIIT-A/HIIT-AR would shorten MT.

For the regular foreperiod trials, in which the foreperiod duration was a constant 2500ms, there was no significant group effect on mRT, mPMT, or mMT. However, it should be noted that both exercise groups had faster times following exercise compared to their baseline results. Therefore, it still appears that acute exercise may have some effect on reaction time. The lack of statistical difference could be explained by the relatively easy nature of this task with the regular foreperiod. Also, in the regular foreperiod trials, there could have been more opportunity for anticipatory responses, thereby lessening the magnitude of variation in the central processing speed between groups.

Unlike the regular foreperiod conditions, there was a significant interaction between group and time for mRT and mPMT for the irregular foreperiod conditions. Both exercise groups had significantly faster mRTs and mPMTs compared to the control group. Specifically, the significantly shorter mPMTs in both exercise groups suggest that the central processes involved in RT were shortened most likely as a result of increased arousal rather than mechanisms impacting muscle activation. No significant change was noted for mMT. However, similar to the regular foreperiod conditions, mMTs were shorter following exercise compared to baseline values. The irregular foreperiod task appears to have been a more appropriate difficulty level for healthy young adults to differentiate between groups.

CHAPTER 6: MOTOR SKILL ACQUISITION

Task and Procedure

Motor skill acquisition was measured on a Biopac MP100 data acquisition and analysis system with Acqknowledge software (BIOPAC Systems, Inc., Goleta, CA). For this test, participants first performed 3 maximal voluntary contractions using a grip dynamometer (Takei Kiki Kogyo, Japan). The highest MVC was entered into Microsoft Excel to create 2 force curves at 70% of their peak MVC. 70% of MVC was chosen for this task as there is a linear relationship between force and its variability around this intensity (Newell & Carlton, 1985; Sherwood & Schmidt, 1980). It has been hypothesized that there is no “room” for variability if intensity gets too close to maximum (Schmidt & Lee, 2011). Participants were instructed to squeeze the dynamometer to match the overall shape (height and width) of the target force curve. Participants were allowed to see their curve in comparison to the target curve, which facilitated adjustment for subsequent trials. During the baseline visit, participants performed 1 block (10 total trials) to establish a baseline for acquisition ability. During the second testing session, participants performed 5 blocks (50 total trials) to measure motor skill acquisition.

Data Processing

To process each curve, the highest peak amplitude was selected and then 49 data points preceding and 49 data points after the peak amplitude were selected to represent the full trial curve (99 total data points). Total performance error (E) was then calculated for each curve (10 curves for practice and 50 curves for acquisition blocks) using the equation $E = \text{Sqrt}(\sum[X_i - T_i]/n)$ where X_i is actual performance, T_i is target performance, and n is total number. Ten curves were averaged together for each block resulting in one practice block and 5 testing blocks.

Statistical Analysis

Baseline E was analyzed using a one-way ANCOVA controlling for cardiovascular fitness. For the second visit, motor skill acquisition E was analyzed using a mixed 3 (control group, HIIT-A group, and HIIT-AR group) x 5 (blocks) ANCOVA controlling for cardiovascular fitness. If any significant interaction was found, univariate ANCOVAs were conducted to investigate main effects. Bonferroni post hoc analyses were conducted to perform pairwise comparisons. All statistical analyses were performed using SPSS (IBM SPSS Statistics, Version 25). Statistical significance was set at $p < 0.05$.

Results

Before conducting analyses, all data were screened for any outliers and normality. E was normally distributed for each group on all blocks, as assessed by Shapiro-Wilk's test ($p > 0.05$) and visual inspection of the data. Additionally, Levene's test of homogeneity of variance for all blocks was not significant ($p > 0.05$), and there was homogeneity of covariances assessed by Box's test of equality of covariance matrices ($p > 0.05$) for baseline and acquisition blocks. E (mean ± standard error) for each block can be found in Table 7. For the baseline block, there were no significant differences between groups on E, $F_{(2, 56)} = 1.765$, $p = .181$, partial $\eta^2 = .059$. For the trial blocks, there was a significant interaction between group and blocks on E, $F_{(8, 216)} = 2.155$, $p = .032$, partial $\eta^2 = .074$. A significant simple main effect of group on E was observed for Block 1 ($F_{(2, 56)} = 3.996$, $p = .024$, partial $\eta^2 = .125$), Block 2 ($F_{(2, 56)} = 3.800$, $p = .028$, partial $\eta^2 = .119$), and Block 3

($F_{(2, 56)} = 3.325$, $p = .043$, partial $\eta^2 = .106$). No significant simple main effect of group was observed for blocks 4 and 5. Bonferroni post hoc analyses were conducted for blocks 1-3 and revealed that the HIIT-A group has significantly less error compared to the control group ($p < 0.05$). No differences were found between the exercise groups or the HIIT-AR and control group ($p > 0.05$). Results can be observed in Table 7 and Figure 17.

Table 7. Total Performance Error during Motor Skill Acquisition by Block.

	Baseline Block	Block 1	Block 2	Block 3	Block 4	Block 5	*d*
Control (n = 19)	9.97 ± .75	9.96 ± .72	9.54 ± .65	9.56 ± .67	9.84 ± .67	9.87 ± .67	-0.11
HIIT-A (n = 21)	8.40 ± .71	7.09 ± .69*	7.05 ± .62*	7.15 ± .64*	7.53 ± .63	7.57 ± .64	-0.41
HIIT-AR (n = 20)	10.17 ± .70	9.01 ± .68	8.75 ± .61	8.84 ± .63	8.85 ± .62	8.93 ± .63	-0.36

Note: All values are presented in mean ± SE
Cohen's d is average E across acquisition blocks – baseline block
**p < 0.05 Bonferroni post hoc results; significantly different from control*

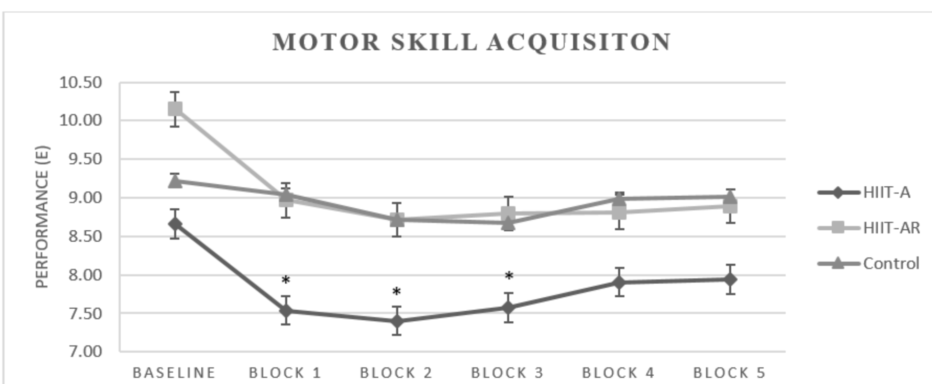

Figure 17. Total Performance Error by Block

Summary

The findings from this study support that all groups reduce error over time compared with the practice block. This study also supports the hypothesis that acute HIIT-

A improves motor skill acquisition compared to a control condition. Participants in the HIIT-A group displayed lower total error (E) on the first 3 blocks compared to the control group. The lack of significance for blocks 4 and 5 was actually due to the HIIT-A group doing slightly worse compared to their performance on blocks 1-3. This may be explained by lack of effort or increased fatigue due to the length of the task (50 trials). The findings from this study did not support the hypothesis that acute HIIT-AR significantly decreases performance error compared to the control group. It should, however, be noted that the HIIT-AR group had more error during the baseline blocks but did improve more than the control group during the acquisition phase. Where the HIIT-AR group showed improvement across the blocks, the control group's performance remained relatively constant. It is possible that a floor effect was observed during this task and that a less difficult task might have discriminated more clearly between the HIIT-AR group and the control group.

CHAPTER 7: EXECUTIVE FUNCTION

Task and Procedure

Executive function was measured via a task switch paradigm on a desktop computer (Dell, Windows XP) using E-Prime 2.0 software (Psychology Software Tools, Pittsburgh, PA). In this task, the first trial block asked participants to judge whether a number on a blue screen (1, 2, 3, 4, 6, 7, 8, or 9) was low or high (i.e., smaller or larger than 5). Then, the second trial block asked participants to judge whether a number on a pink screen (1, 2, 3, 4, 6, 7, 8, or 9) was odd or even. Finally, the third block asked participants to switch between either deciding if a number was low or high or odd or even based on the background color of the number (Figure 18). Participants completed one practice block before performing the actual test for each condition. Numbers were presented individually for 1500 milliseconds against a pink or blue background at the center of the screen, and the same number was never allowed to appear twice in succession. Reaction time and accuracy were measured for both the single and mixed trial blocks.

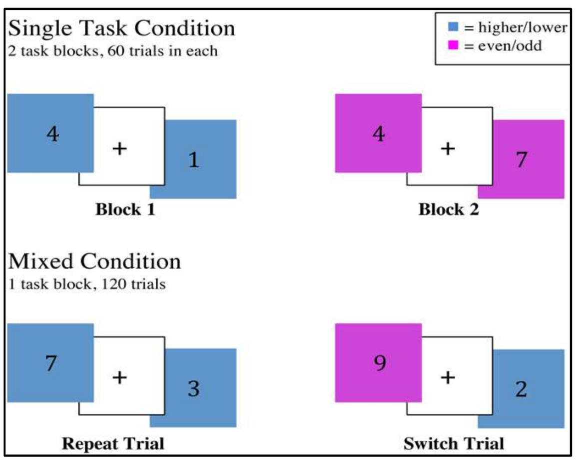

Figure 18. Executive Function Task

Statistical Analysis

For executive function, dependent variables were reaction time and accuracy. Data were analyzed for single choice trials and mixed trials (both high/low and odd/even). Data were analyzed using a mixed 3 (control group, HIIT-A group, and HIIT-AR group) x 2 (pre- and posttest) ANCOVA controlling for cardiovascular fitness. If a significant group by time interaction was found, one-way ANCOVAs were performed to investigate the simple main effect of group allocation. A Bonferroni test was used when appropriate to determine differences between groups (control, HIIT-A, and HIIT-AR). Statistical analyses were performed using SPSS (IBM SPSS Statistics, Version 25). Statistical significance was set at $p < .05$.

Results

Prior to analyses, data were screened for outliers and normality. Significant outliers were excluded from all analyses. Reaction time data (Mean ± SE) is presented in Table 8.

Reaction Time

At baseline, when controlling for cardiovascular fitness, there were no significant differences between the groups for single trial reaction time ($F_{(2, 48)} = .593$, $p = .556$, partial $\eta^2 = .021$) or mixed trial reaction time ($F_{(2, 48)} = .415$, $p = .662$, partial $\eta^2 = .015$). Following the intervention, there was a significant interaction between group and time for the single trial conditions, $F_{(2, 48)} = 4.132$, $p = .022$, partial $\eta^2 = .147$. A simple main effect of group was noted $F_{(2, 48)} = 6.779$, $p = .003$, partial $\eta^2 = .220$, with post hoc analyses showing that the HIIT-A group (M = 582, SE = 27) was significantly faster than the control group (M = 708, SE = 25). No differences were reported between the HIIT-A and HIIT-AR group (M

= 633, SE = 22). For the mixed trials, there was no significant interaction between group and time ($F_{(2, 48)} = .871$, $p = .425$, partial $\eta^2 = .035$). When the mixed trials were separated, this also held true for both switch trials ($F_{(2, 48)} = .886$, $p = .419$, partial $\eta^2 = .036$) and repeat trials ($F_{(2, 48)} = 1.554$, $p = .222$, partial $\eta^2 = .061$).

Table 8. Reaction Times for Single and Mixed Trials

	Control (n=15)			HIIT-A (n=18)			HIIT-AR (n=19)		
	Pre	Post	*d*	Pre	Post	*d*	Pre	Post	*d*
Single	645 ± 22	708 ± 25	0.57	598 ± 18	582 ± 27**	-0.18	638 ± 16	633 ± 22	-0.07
Mixed	964 ± 29	924 ± 37	-0.29	931 ± 25	844 ± 24	-0.70	978 ± 26	925 ± 22	-0.47

Note: All values are presented in milliseconds (mean ± se)
Cohen's d is post-pre
***Significantly different from control (p < 0.01)*

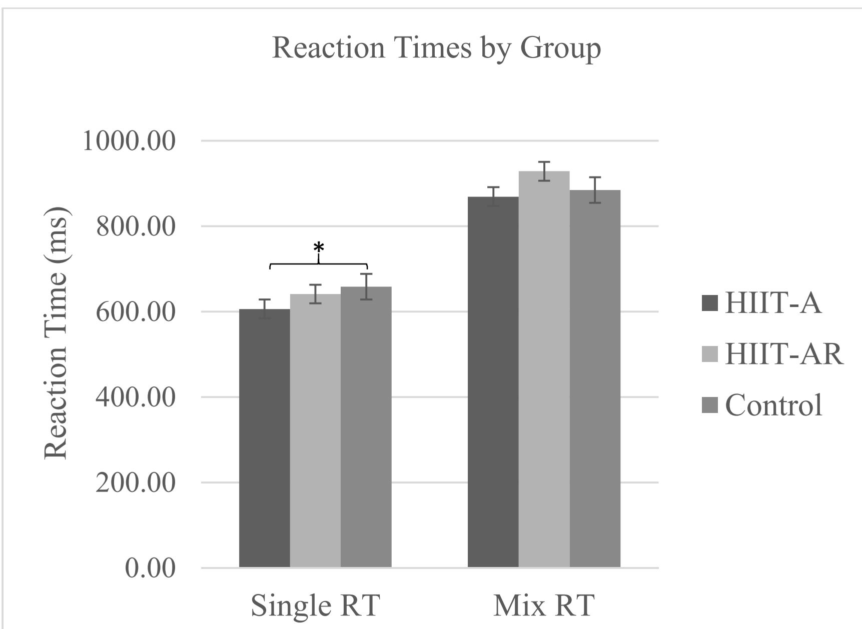

Figure 19. Single and Mixed Trial Reaction Time Results

Accuracy

Accuracy data (mean ± SE) are presented in table 9. At baseline, when controlling for cardiovascular fitness, there were no significant differences between the groups for single trial accuracy ($F_{(2, 48)}$ = 1.043, p = .359, partial η^2 = .036) or mixed trial accuracy ($F_{(2, 48)}$ = .323, p = .725, partial η^2 = .011). Following the intervention, results indicated that, for accuracy, there was no interaction between group and time for the single trial condition, $F_{(2, 48)}$ = .524, p = .596, partial η^2 = .021. For the mixed trials, there was a significant interaction between group and time, $F_{(2, 48)}$ = 3.535, p = .037, partial η^2 = .128. There was a significant simple main effect of group allocation on mixed trial accuracy, $F_{(2, 48)}$ = 5.570, p = .006, partial η^2 = .193. Post hoc analyses revealed that the HIIT-A group (M = .981, SE = .01) and HIIT-AR group (M = .970, SE = .01) had significantly fewer incorrect responses compared to the control group (M = .940, SE = .01). There was no significant difference between the exercise groups (p > .999). When the mixed trials were separated, there was no interaction between group and time for either switch trials $F_{(2, 48)}$ = 2.943, p = .062, partial η^2 = .109, or repeat trials, $F_{(2, 48)}$ = 1.778, p = .180, partial η^2 = .069.

Table 9. Accuracy Results for Single and Mixed Trials

	Control (n=15)			HIIT-A (n=18)			HIIT-AR (n=19)		
	Pre	Post	*d*	Pre	Post	*d*	Pre	Post	*d*
Single	.957 ± .01	.960 ± .01	0.05	.957 ± .01	.984 ± .01	0.48	.965 ± .01	.977 ± .01	0.33
Mixed	.945 ± .01	.940 ± .01	-0.12	.937 ± .01	.981 ± .01**	0.86	.940 ± .01	.970 ± .01*	0.65

Note: All values are represented as percent correct
Cohen's d is post-pre
**Significantly different from control (p < 0.05)*
***Significantly different from control (p < 0.01)*

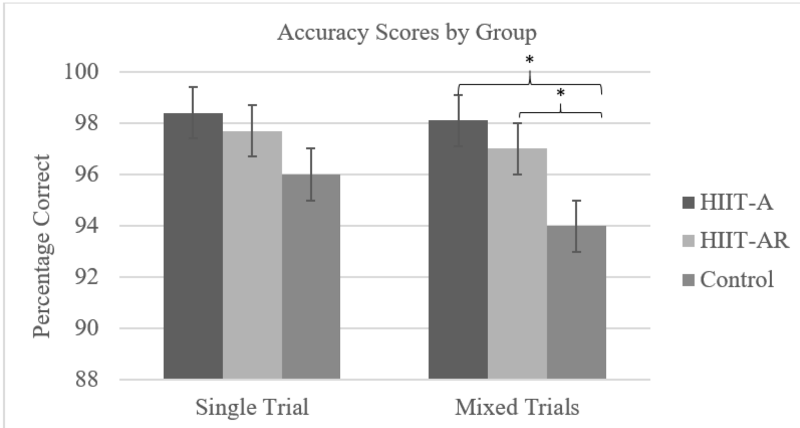

Figure 20. Single and Mixed Trial Accuracy Results

Summary

The findings from this study support the hypothesis that acute HIIT leads to reduced reaction time during executive function tasks. However, the findings only showed significantly reduced reaction times for the HIIT-A group. Moreover, reaction time was only reduced for the single choice trials and not for the mixed trials. The results from this study also support the hypothesis that both exercise groups would have significantly fewer errors on measures of executive function compared to the control group. Both exercise groups had significantly fewer errors compared to the control group on the mixed trial block. There was no difference in accuracy for the single trial blocks.

CHAPTER 8: GENERAL DISCUSSION

The primary objective of this study was to investigate the acute effects of high-intensity interval training (HIIT) on postural control, information processing, motor skill acquisition, and executive function in healthy young adults. The results demonstrate that a single bout of HIIT leads to significant improvements in components of information processing, motor skill acquisition, and executive function compared to a resting control group. The exercise interventions were not found to have any significant effect on measures of postural control.

The secondary objective of this study was to explore the impact of HIIT utilizing two distinct exercise intervention protocols: (1) aerobic only and (2) combination aerobic and resistance exercise. The findings from this study support that HIIT is a time-efficient form of exercise that can provide similar improvements in motor function and cognitive abilities to those observed following longer bouts of light-moderate aerobic exercise. Based on the results, the different exercise protocols produced similar effects on information processing speed, but HIIT-A appears to have a greater impact on motor skill acquisition and executive function. In the following sections, each of these findings will be discussed in more detail.

Postural Control

The results from this study did not support the hypothesis that acute HIIT would improve postural control. It was hypothesized that acute HIIT might serve as a primer for the nervous system and thereby lead to improvements in postural control. It was additionally thought that acute exercise would provide a strong sensory stimulus, activate muscle spindles, and ultimately improve proprioception and postural control just as other interventions like whole-body vibration training have been shown to do (Bogaerts, Verschueren, Delecluse, Claessens, & Boonen, 2007). However, analyses did not support these theories.

There are limited and overall inconsistent data on the effects of exercise on postural control in the literature. Previous research has demonstrated that postural control is reduced immediately following a single bout of intense exercise and that impairments in postural control can remain for up to 60 minutes post-exercise (Egerton et al., 2009; Foulis, Jones, van Emmerik, & Kent, 2017; Moore et al., 2005). Other studies (including the present one) have reported that submaximal exercise does not negatively affect postural control and postural stability (Palm, van Uden, Riesner, Lang, & Friemert, 2015; Raj, Westfold, Shield, Linden, & Bird, 2014). Notably, previous studies have primarily focused on older adults and other populations at increased risk for falls and stability issues. To this point, data on the effects of acute exercise on postural control in young adults is much more limited.

In younger adults (mean age = 19), one study found that postural disturbances persist for up to 13 minutes following aerobic and anaerobic exercise (Fox et al., 2008). However, the researchers utilized exercise protocols in this study which were specifically designed to elicit high levels of fatigue in order to ensure detrimental effects on postural control. A more recent study asked participants to complete 30 minutes of treadmill running at anaerobic threshold and found that all negative impact on postural control resolved within 10 minutes of exercise cessation (Guidetti et al., 2011). The results of the present study are consistent with these results: although both exercise groups reached high intensities during exercise (80-85% age predicted maximum heart rate), an active cool down followed by a 10-minute passive recovery period provided sufficient recovery time to negate negative effects of exercise on postural control assessments.

After initial analyses demonstrated no significant change in postural control following acute exercise, closer examination of the data was performed to look for trends (i.e., direction of change from pre- to post-test). No such trends, positive or negative, were found. These results suggest that acute exercise with adequate recovery had neither a positive nor negative effect on postural control. These findings highlight that, despite the potential of exercise to improve cognitive factors which contribute to postural control like information processing, benefits beyond these effects may not be acutely and easily observable on gross motor tasks. It is also possible that the tests employed in this study to assess postural control may be more appropriate to measure changes over time rather than acute variations in postural stability.

Another possible explanation for the lack of measurable difference in postural stability following exercise may be related to task difficulty. In this study, both postural control assessments were performed on a firm surface. In other studies of younger adults, researchers have opted to use less stable surfaces like a foam pad to increase task difficulty (Larson & Brown, 2018). Additionally, as discussed previously, assessments of postural control via measurement of sway (the horizontal movement of the center of gravity) are challenging because an individual's center of gravity is not easily determined (Horak, 1987; Murray et al., 1967). Even very complex and significant compensatory methods to maintain balance might produce only a very small measurable movement of the center of gravity (Horak, 1987). Therefore, given these challenges, it is possible that positive or negative effects of exercise on postural control could exist but were simply not detected by the measurements utilized in this study. Increasing the difficulty of the assessment could improve the sensitivity of sway measurement and potentially provide clarity about the effects of exercise (if any) on postural control. Varying degrees of task difficulty were utilized in this study via the removal of visual input, but even for the eyes-closed trials, there were still not significant differences between or within the groups.

Overall, the body of evidence on exercise and postural control is quite limited, and more research is needed to understand effective testing of postural stability for optimum sensitivity and, ultimately, to determine if acute exercise, followed by adequate rest, could be used to improve postural control. The results from this study, in addition to previous research, suggest that if assessing postural control following intense exercise within young adult populations, a recovery period of 10-15 minutes is sufficient to allow recovery of postural control (Guidetti et al., 2011). Future research focused on postural control and exercise should utilize measures that place greater demands on the postural system to allow more sensitive detection of acute changes in postural control.

In addition to acute exercise, very little is known about the effects of chronic training (> 2 years) on postural control in young adults. Similar to acute exercise, it is accepted that chronic exercise training seems to have many global benefits on the motor cortex which would imply improvements in motor function and motor control, yet research is needed to understand these effects at the behavioral level (Cirillo, Lavender, Ridding, & Semmler, 2009). Understanding the effects of acute and chronic training could highlight important relationships between exercise and postural control which ultimately would provide support for the importance of consistent exercise habits in younger adult populations.

Information Processing

The results of this study demonstrate that acute exercise leads to improved information processing speed. These findings are consistent with previous research showing that both acute aerobic exercise and acute resistance exercise can have a moderate effect (η^2 = .151) on RT (Audiffren et al., 2008; Lambourne & Tomporowski, 2010; Tomporowski, 2003). In this study, significant differences in RT were observed only under the irregular foreperiod condition but not the regular foreperiod conditions. For the regular foreperiods, the exercise groups still had faster reaction times after exercise (similar to the irregular foreperiods) while the control group had a slight increase in reaction time during the second visit. However, the lack of significant difference may have been due to higher temporal prediction and a "ceiling effect" on the regular foreperiod condition. These results were not altogether surprising given previous literature showing that RT increases when there is greater uncertainty in foreperiod length and decreases when stimuli are presented in a more predictable manner (Klemmer, 1956; Niemi & Näätänen, 1981; Nissen & Bullemer, 1987). In the present study, the regular foreperiod condition may have allowed for more anticipatory responses, allowing the PMT to reach a ceiling level, while the irregular foreperiod condition, with its low predictability, led to longer time for the central processing and allowed more room for improvement following exercise. Future research examining information processing via RT in healthy young adults could benefit from the selection of a task with sufficient difficulty and variability to detect effects of acute exercise with increased sensitivity.

Prior to the present investigation, several studies have examined the effects of acute exercise on RT and information processing (Chang et al., 2012; Tomporowski, 2003). However, only a few had integrated EMG to fraction reaction time and explored individual components of processing speed (Audiffren et al., 2008; Beyer et al., 2017; Chang, Etnier, & Barella, 2009; Davranche et al., 2005; Davranche et al., 2006). Fractioning reaction time is critical to determine which components of RT (PMT and MT) are affected by exercise. Moreover, this method allows researchers to make inferences about the effects of exercise on arousal and activation mechanisms in the central nervous system and the peripheral neuromuscular system (Sternberg, 1969).

Previous studies have shown that acute exercise reduces MT via muscle activation but exerts little effect on PMT (Audiffren et al., 2008; Sanders, 1983). Based on their findings, these researchers have suggested that a single bout of exercise selectively influences muscle activation but not arousal. Contrary to these previous findings, the results of this current study demonstrate a significant reduction in PMT following acute exercise, but a non-significant reduction in MT following exercise. These findings more closely align with those of Clarkson (1978), who found that exercise impacts MT far less than it impacts PMT. Moreover, it has been well established that PMT accounts for about 70% of reaction time while MT only accounts for about 30%, implying that exercise's impact on RT is more likely due to its impact on PMT rather than on MT (Baylor & Spirduso, 1988). Furthermore, other studies have demonstrated that acute exercise improves flicker fusion frequency, which is sensitive to changes in level of arousal (Davranche & Audiffren, 2004; Davranche et al., 2005; Davranche & Pichon, 2005). Although these studies did not utilize EMG, results still support the effect of exercise on arousal and certainly imply reduced RT following exercise may be due to reduced PMT. The findings of this present study agree with these conclusions and add support to the notion that acute exercise leads to increased levels of arousal and ultimately reduces RT via significant reductions in PMT.

Although the findings of this study differ from recent EMG research on the topic, differences may be attributed to factors like the type and duration of exercise studied, the type of cognitive task employed, and the timing of the cognitive assessments. Lambourne and Tomporowski (Lambourne & Tomporowski, 2010) aptly stated that the relationship between exercise and cognition is so complex that all of these factors need to be considered when interpreting results and making comparisons among studies. In previous studies investigating the impact of exercise on fractioned RT, cycle ergometry was utilized as the sole mode of exercise, while the present study asked participants to engage in body weight exercises requiring greater control of their movements (Audiffren et al., 2008; Beyer et al., 2017; Chang et al., 2009; Davranche et al., 2005; Davranche et al., 2006). The use of exercises requiring the integration of a number of senses (vestibular, visual, and somatosensory) could conceivably have impacted arousal and central processes rather than motor processes alone. Furthermore, it has been suggested that exercises requiring more body awareness may result in greater overall levels of attention, which would also yield improved performance on cognitive tasks (Gothe et al., 2013). Therefore, the use of exercise protocols involving novel and challenging exercises may have had a more significant impact on information processing speed through changes in PMT. Research on chronic exercise involving more demanding exercises (like dance) suggest different cognitive effects than those associated with solely aerobic exercise (like cycling) (Kattenstroth, Kalisch, Holt, Tegenthoff, & Dinse, 2013; Kattenstroth, Kolankowska, Kalisch, & Dinse, 2010; Rehfeld et al., 2017). Although these studies focused on the impact of chronic exercise, they suggest that acute aerobic exercise with similarly demanding cognitive/learning components may also yield acute cognitive effects that alter PMT and ultimately reduce RT. Further research comparing exercise protocols such as the ones used in this study to more commonly utilized exercise interventions (e.g., steady state cycling) is needed to support more definitive conclusions on this hypothesis.

In addition to mode of exercise, the type of cognitive task employed is also an important variable to consider when assessing the impact of exercise on cognition. There is, in fact, wide variation among tasks used by researchers attempting to determine the effect of acute exercise on RT. Audiffren et al. (2008) utilized a task that provided auditory stimulus and required participants to be prepared to respond physically with either their left or right hands. Beyer et al. (2017) used a visual task but again required the participants to raise either their left or right hand in response. Both tests included an accuracy component and required fairly long movement times to complete a response. In contrast, the task utilized in the present study required substantially less physical movement without any accuracy component, which resulted in shorter mean RTs when compared to these other studies. This could explain why these studies observed only an impact on MT following acute exercise, since their chosen tasks required a much longer movement time.

In addition to differences in MT, tasks that have both a speed and an accuracy component are also prone to the phenomenon known as the speed-accuracy tradeoff, which simply states that, in order to increase accuracy, one might compromise speed and vice versa (Schouten & Bekker, 1967; Wickelgren, 1977). When precision in the measurement of RT, PMT, and MT are important to the conclusions of a study, this may be problematic since it has been hypothesized that highly accurate performances may be achieved by adopting a more sensorial set but also slower response times (Rinkenauer, Osman, Ulrich, Müller-Gethmann, & Mattes, 2004). If participants were first and foremost concerned with making a correct response, PMT may have slowed down in order to ensure accuracy, leading only to observable differences during the MT. This has the potential to skew results based on the focus of the individual participants, and may limit the generalizability and comparison of the aforementioned studies.

In the present study, there was no accuracy component and the physical response expected of participants was limited to movement of a single thumb. The simplicity of the task allowed study subjects to focus on a singular goal and thereby avoid the confounding factors that have perhaps made interpretation of data difficult in some previous studies. The task used in the present study is similar to that previously utilized by Davranche et al. (Davranche et al., 2005; Davranche et al., 2006). Although the primary finding of their study was that acute exercise significantly reduces MT during a simple choice reaction time task, the researchers also examined differences in visual stimulus intensity and found that exercise impacted PMT as well. The researchers concluded that, although the observed effect was small, exercise did appear to have an impact on central sensory processes in addition to peripheral motor processes.

The findings of the present study support those of previous research and add to the body of evidence demonstrating the effect of acute exercise on RT. Based on the results, it is clear that acute HIIT-A and HIIT-AR elicit similar improvement in information processing and thus may be effective alternatives to steady-state aerobic exercise when this is the goal. The data also highlight the way in which the type and duration of exercise, as well as the specific cognitive task evaluated, may affect different stages of the information processing model (Lambourne & Tomporowski, 2010; Sanders, 1983). Therefore, this study affirms previous statements that there is a highly complex relationship between exercise and cognitive functioning, and re-emphasizes the need for further investigation into how acute exercise influences various sensory and cognitive processes (Audiffren et al., 2008; Lambourne & Tomporowski, 2010). Studies on exercise and information processing should continue to use EMG to discover with the most precision which cognitive processes are affected by acute exercise and how the associated mechanisms impact RT.

Motor Skill Acquisition

The findings from this study suggest that acute HIIT-A has a significant impact on motor skill acquisition. At baseline, there was no significant difference in total error between the groups. Following exercise, the HIIT-A group had significantly lower error for blocks 1-3 compared to the control group. By blocks 4 and 5, there was no longer a difference between the groups. For this motor cognitive measure, HIIT-AR group did not show significant differences compared to the control group. Although there was no statistically significant difference in motor skill acquisition between the HIIT-AR group and the control group, the HIIT-AR and HIIT-A groups did show similar improvements in accuracy during the acquisition blocks. Both exercise groups had about a 14% reduction in total performance E compared to the baseline block while this reduction was only about 3% in the control group. Given this, it is likely that HIIT-AR may also lay the groundwork for improved motor skill acquisition like HIIT-A. However, future research on this topic may benefit from randomization based on total error at baseline to ensure the groups are more consistent in this respect before measuring motor skill acquisition.

To date, several studies have examined the effects of acute exercise on cognitive functions. However, the effects of acute exercise on behaviors involving the motor cortex such as motor learning have received little investigation (Basso & Suzuki, 2017). The findings from this study support the available previous literature which concluded that acute exercise improves motor skill acquisition (Mang et al., 2014; Statton et al., 2015). These results differ from those of other studies which found only an improvement in motor skill retention following exercise (Roig et al., 2012). The inconsistent results of these studies are likely related to variability in tasks used for assessment of motor skill acquisition. Roig et el. (2012) used a visuomotor accuracy tracking task in which participants were asked to track a torque signal displayed on a computer screen. The speed of the signal was fixed in this task, so participants only needed to be concerned with their overall accuracy (correctly tracing the reference line). In the present study, however, participants were asked to replicate a curve by squeezing a handheld dynamometer. In this task the speed was not fixed, so participants needed to adjust both how much force they applied as well as how quickly or slowly they applied that force. The increased difficulty of this task may have allowed for greater sensitivity in the detection of differences between groups during acquisition. This task was similar to that used by Statton et al. (2015), who also were able to detect significant improvements in motor skill acquisition following moderate intensity exercise in their study.

Researchers have hypothesized various mechanisms to explain exercise's role in improving motor skill acquisition. In previous literature, exercise has been associated with increased levels of arousal as well as better allocation of attentional resources which facilitate improved cognitive performance (Audiffren et al., 2008, 2009). According to the hypofrontality hypothesis, the control and maintenance of movement demand considerable metabolic resources (Dietrich, 2003). Therefore, on tasks which require significant cognitive control like the one used in this study (i.e., the ability to configure and adjust performance based on feedback), the increased arousal and better allocation of attentional resources to more active cortical networks resulting from exercise leads to enhanced performance.

A second mechanism that has been proposed involves increased concentration of serum proteins such as brain-derived neurotrophic factor (BDNF). Researchers have observed increased BDNF concentration following intense exercise and have suggested that BDNF mediates the effect of exercise on motor learning (Knaepen, Goekint, Heyman, & Meeusen, 2010; Skriver et al., 2014). BDNF is known to have an important role in motor skill acquisition and memory as it regulates both excitatory and inhibitory synapses in the CNS (Cunha, Brambilla, & Thomas, 2010). And this increase in synaptic activity within areas like the motor cortex has been associated with improved motor skill acquisition and retention (Mang et al., 2013). Although evaluation of these underlying mechanisms was beyond the scope of the present study, the observed effects of exercise on cognitive function and motor skill acquisition are likely a result of increased levels of arousal, better allocation of attentional resources to active cortical networks, and increased concentration of neurotrophic proteins like BDNF.

The beneficial effects of exercise on motor skill acquisition demonstrated in this study and in earlier research could have important implications for the future of physical rehabilitation (Mang et al., 2013; Statton et al., 2015). For example, there may be opportunities to enhance the capacity of patients to efficiently acquire motor skills by including exercise in a therapy session before the practice of a motor skill. When patients learn (or relearn) a motor skill, the ability to utilize feedback and make necessary corrections and adjustments is important for adequate learning (Kawato, 1990). As reported in previous literature, it appears even a single bout of exercise is sufficient to prime the nervous system, improve cognitive control, and ultimately enhance both acquisition and retention of a motor skill.

It is important to note that the participants in this study were relatively young, healthy, and fit individuals, which may limit the generalizability of these findings to other populations. Additionally, the exercise protocol used in this study was high intensity and thus may not be appropriate for less physically fit individuals and special clinical populations. It has been noted that exercise impacts cognitive abilities in a U-shaped fashion—that moderate exercise has beneficial effects while exercise that is too intense may have negative outcomes (Brisswalter et al., 2002; Kashihara, Maruyama, Murota, & Nakahara, 2009). While the findings from this study suggests that the HIIT protocol was not too intense for this young adult sample, this specific protocol requires further investigation in other populations to investigate how well it is tolerated and in what manner (positively or negatively) it impacts motor skill acquisition for those populations.

Executive Function

The final task participants completed in this study was a measure of executive function. A task switching test was used for this study to assess participants' ability to switch between different mental sets. For the single task blocks, the HIIT-A group had significantly faster reaction time compared to the control group. No difference was observed between the HIIT-AR group and the control group. Additionally, no differences in error were observed between the groups on the single task trials due to the simple nature of the task and high accuracy of all groups. For the mixed trials, differences were observed on accuracy measures, with both exercise groups having significantly fewer errors compared to the control group. No differences in reaction time were observed between the groups on mixed trials.

The findings from this study support numerous studies reporting that acute exercise improves time-dependent measures and accuracy measures of executive function tasks (Lambourne & Tomporowski, 2010; Ludyga, Gerber, Brand, Holsboer□Trachsler, & Pühse, 2016a). Although some researchers have reported that the impact of exercise on executive functioning is not as notable in young adults, this study still found moderate to large effects ($\eta^2 = .193$) of exercise on response time and accuracy in this young, healthy cohort (Chang et al., 2012). All groups had improved response times and accuracy on the second visit. But greater change in both response time and accuracy was observed for those in the exercise groups. In a meta-analysis by McMorris and Hale (2012), researchers reported that increased arousal following moderate-intensity exercise resulted in faster processing speed but yielded minimal effects on accuracy. They hypothesized that exercise-induced arousal most likely does improve accuracy, but that previous studies had not utilized a task with sufficient difficulty to detect the change. The task-switching task used in this study was able to capture improvements in both response time and accuracy, demonstrating that a single bout of HIIT exercise significantly improves executive functioning. For both trials (single and mixed), there was no speed accuracy trade-off observed.

This study is unique in that it is one of the first to examine the effects of a single session of HIIT training on executive functioning. Previous research has more commonly used steady-state aerobic exercise and traditional weight resistance training on exercise machines; only recently have researchers begun investigating other modes of exercise such as HIIT. The findings from this study are consistent with those of previous studies, and show that HIIT exercise improves executive functioning in young adults (Tsukamoto, Suga, Takenaka, Tanaka, Takeuchi, Hamaoka, Isaka, & Hashimoto, 2016a; Tsukamoto, Suga, Takenaka, Tanaka, Takeuchi, Hamaoka, Isaka, Ogoh, et al., 2016b). Interestingly, the executive function task was the final task participants performed (about 25 minutes following completion of exercise.) Despite this gap, significant improvement in executive functioning was still observed for the exercise groups compared to the control group This too is consistent with previous research, which has demonstrated that the positive effects of HIIT on executive functioning persist for up to 30 minutes following exercise (Tsukamoto, Suga, Takenaka, Tanaka, Takeuchi, Hamaoka, Isaka, & Hashimoto, 2016b).

Exercise protocols from previous studies looking at HIIT and executive functioning utilized much longer work to rest ratios (4 minutes higher intensity, 3 minutes lower intensity) and were performed on a cycle ergometer. In this study, work to rest ratios were much shorter, similar to earlier research on HIIT, and the exercise protocols utilized bodyweight exercises (Tabata et al., 1996). Additionally, in previous studies, work and rest were prescribed to each participant based on their VO_{2Peak} whereas participants in this study were asked to push themselves based on their comfort level (Mang et al., 2013; Tsukamoto, Suga, Takenaka, Tanaka, Takeuchi, Hamaoka, Isaka, & Hashimoto, 2016a). Modified versions of each exercise were also provided so participants of all fitness levels could participate and complete the exercise protocol. Given these key differences in study design, this study adds to the literature by demonstrating that other forms of exercise (bodyweight training) using very short work to rest ratios (20:20 seconds) can significantly improve cognitive functioning just as more traditional exercise protocols are known to do. The findings of this study may thus be more relevant to real-world settings in which exercise is not prescribed for individual patients but rather needs to be generalizable within a group. Although this study was only designed to detect the impact of HIIT on reaction time and executive functioning, other recent research has indicated that HIIT may similarly improve other cognitive abilities such as memory, selective attention, and inhibitory control (Kao, 2017; Kao et al., 2017; Tsukamoto, Suga, Takenaka, Tanaka, Takeuchi, Hamaoka, Isaka, & Hashimoto, 2016a; Walsh et al., 2018). Given all of this, despite limited evidence so far, HIIT is a promising mode of exercise which is time-efficient and holds the potential to promote a range of cognitive benefits after only a single session.

Limitations

Though the findings of this study are supported by previous research in the area, there remain limitations that could potentially limit the validity and generalizability of results. First, participants in this study performed the cognitive tasks in a specified order, which could have impacted the observed results. For example, a different effect may have been observed on motor skill acquisition if it was performed first following completion of the exercise session. Similarly, results of the executive function measure could have been stimulated by the motor task performed immediately prior, rather than by the exercise intervention itself. Additional research should further investigate the acute effects of exercise and how timing of various cognitive and motor tasks following exercise is affected. Second, all participants in this study were between the ages of 18 and 40 years old. Although the findings of this study certainly could have important implications for other populations (e.g., older adults and clinical populations), additional research on this specific HIIT protocol is needed to understand how other populations tolerate it. Still, since positive results were found in this both high physically- and cognitively-fit sample, acute HIIT could have even more significant results in populations with greater room for improvement and greater potential to benefit from an exercise intervention. Lastly, the effects of exercise on motor and cognitive abilities were assessed in a controlled laboratory environment. The effects of exercise on motor control and cognitive function in actual rehabilitation settings is warranted.

Conclusion

In conclusion, the findings from the study support the hypotheses that acute HIIT causes significant improvements in information processing speed, motor skill acquisition, and executive function in healthy, young adults. This study did not support the hypothesis that acute HIIT improves postural control, though this finding could be attributable to the use of a task which was too easy for this population. Overall, the results from this study support that the utility of a short bout of HIIT utilizing bodyweight exercises for improving both cognitive and motor functions. Acute HIIT seems to be a sufficient form of movement-based priming to render it useful for improving motor skill acquisition in rehabilitative settings. Furthermore, the HIIT protocol used in this study may be more practical for use with large groups or in settings with limited exercise equipment. Ongoing research should continue to investigate this form of HIIT and others in populations which have the most potential to benefit from improved rehabilitation and motor learning strategies. Additional research should also assess other characteristics of exercise (e.g., type, intensity, duration) and how they differently affect motor function and motor learning.

APPENDIX A: APPROVAL LETTER

WAYNE STATE UNIVERSITY

IRB Administration Office
87 East Canfield, Second Floor
Detroit, Michigan 48201
Phone: (313) 577-1628
FAX: (313) 993-7122
http://irb.wayne.edu

NOTICE OF FULL BOARD APPROVAL

To:	Bradley Kendall Kinesiology, Health and Sport Studies 5425 Gullen Mall
From:	Sabrina Heidemann, M.D. or designee S. Heidemann, M.D / 2.2 Chairperson, Medical/Pediatric Institutional Review Board (MP4)
Date:	October 26, 2017
RE:	IRB #: 084717MP4F
	Protocol Title: Acute and Chronic Effects of Aerobic and Resistance Exercise Training on Postural Control and Cognitive Function
	Funding Source: Unit: Kinesiology, Health and Sport Studies
	Protocol #: 1709000813
Expiration Date:	October 25, 2018
Risk Level / Category:	Adult: Research involving greater than minimal risk but presenting the prospect of direct benefit to the subject

The above-referenced protocol and items listed below (if applicable) were **APPROVED** following *Full Board Review* by the Wayne State University Institutional Review Board (MP4) for the period of 10/26/2017 through 10/25/2018. This approval does not replace any departmental or other approvals that may be required.

- Revised Research Protocol and Revised Protocol Summary Form (revision received in the IRB office 10/24/17)
- Medical records are not being accessed therefore HIPAA does not apply
- Medical Research Informed Consent - Experiment 1 (revision dated 10/24/17)
- Medical Research Informed Consent - Experiment 2 (revision dated 10/24/17)
- Academica Advertisement for Experiment 1
- Study Flyer for Experiment 1
- Academica Advertisement for Experiment 2
- Study Flyer for Experiment 2
- Data Collection Tools (6): (I) Baseline Testing Form, (II) Exercise Session Testing Form, (III) Physical Activity Readiness Questionnaire, (IV) Training Status Quesionnaire, (V) BORG Ratings of Perceived Exertion Scale and (VI) Polar Heart Rate Monitor

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- Federal regulations require that all research be reviewed at least annually. You *may* receive a *"Continuation Renewal Reminder"* approximately two months prior to the expiration date; however, it is the Principal Investigator's responsibility to obtain review and continued approval **before** the expiration date. Data collected during a period of lapsed approval is unapproved research and can *never* be reported or published as research data.
- All changes or amendments to the above-referenced protocol require review and approval by the IRB **BEFORE** implementation.
- Adverse Reactions/Unexpected Events (AR/UE) must be submitted on the appropriate form within the timeframe specified in the IRB Administration Office Policy (http://www.irb.wayne.edu/policies-human-research.php).

NOTE:

1. Upon notification of an impending regulatory site visit, hold notification, and/or external audit the IRB Administration Office must be contacted immediately.
2. Forms should be downloaded from the IRB website at **each** use.

Notify the IRB of any changes to the funding status of the above-referenced protocol.

APPENDIX B: INFORMED CONSENT

Effects of Interval-based Exercise on Motor Behavior

[Medical] Research Informed Consent
Title of Study: *Acute Effects of Aerobic and Resistance Exercise Training on Motor Behavior and Cognitive Function*

Principal Investigator (PI): Bradley Kendall
Wayne State University
Division of Kinesiology, Health and Sport Studies
0050 Old Main
Detroit, MI- 48202
Tel: 313-577-4246

Purpose

The purpose of this research study is to examine the effects of high intensity aerobic training and high intensity resistance training on motor behavior and cognitive function. You qualify to take part in the study because you are above 18 years of age, English speaking, have no known learning disabilities, and have answered no to all questions on the Physical Activity Readiness Questionnaire indicating you are healthy and ready to engage in exercise. Our goal is to recruit 60 people and expect at least 45 people to participate in this study.

Please read this form and ask any questions you may have before agreeing to be in the study.

We are interested in examining how interval-based exercise sessions affect motor behavior and cognitive performance in college students.

Study Procedures

If you agree to take part in this research study, you will attend three sessions each lasting 1 hour. Each testing session will take place on Wayne State's campus in the Old Main building. During these testing sessions, you will complete a measure of body composition, two exercise sessions, and tests that measure aspects of motor behavior and cognitive function. Each session will last about 1 hour meaning there is roughly a 3-hour commitment, spread over three days of your choosing, if you wish to participate in this study. All participants will complete the same assessments described in detail below:

Testing Assessments: Visit 1 will consist of basic health measurements taken (weight, height, resting blood pressure, body composition, and resting heart rate. Next, you will complete tests that measure motor behavior such as balance and cognitive function via a reaction time test. First, we will measure your balance by asking you to stand on one leg for up to ten seconds. This will be performed on both your right and left legs. We will then have you repeat this test again but with your eyes closed. Following this task, you will complete a computer-based reaction time task. During this task you, you will be asked to respond as quickly as possible every time that you see a green circle on the screen. During this test we will also be measuring muscle activity. In order to do this, we will place a small pad on your thumb which will be connected to a wire. This is a noninvasive way to measure the electrical activity of the muscle during movement. The third task that you will complete is the motor skill acquisition task. During this task, you will be asked to squeeze a handle and try to match both the force and speed of a curve that is displayed on a computer. You will perform 10 trials in order to try and improve your accuracy. The final task you will perform is an executive functioning task. During this task, you will see either blue or pink numbers on a screen. For blue numbers, you will need to decide if that number is higher or lower than five. For pink numbers, you will need to decide if that number is odd or even. Finally, you will complete a cardiovascular test that measures the maximum amount of oxygen that your body can consume during exercise. During this test, you will be running on a treadmill and we will have you breathe into a tube so we can measure the amount of oxygen that you are consuming.

Visits 2 and 3: You will perform either an interval-based aerobic training session or an interval-based resistance training session. The research staff will contact you before each appointment and inform you about which activity you will perform. On the day of the visit, you will have your basic health measures taken again. Then you will participate in an exercise session lasting 20 minutes of aerobic or resistance exercise. For safety, each session will start with a proper warm up and end with a cool down. The warm-up and cool downs for both sessions will consist of jumping jacks. The other exercises that will be performed during the exercise portion consist of burpees, mountain climbers, high knees, squats, and push-ups. Prior to starting the exercise session, we will walk you through how to safely perform all exercises and provide modifications if the original exercise is too difficult. In addition, we will monitor your heart rate and subjective rating of exertion periodically during the 20 minutes. After the exercise session, you will complete the same tests of motor behavior and cognitive function that you did during visit 1. At any point during the testing sessions, you are free to stop for any reason.

By performing a baseline session first, we will then compare your test results (i.e. balance and cognition) following each exercise session to baseline values in order to determine if exercise improves a person's ability to balance as well as if exercise increases a person's reaction time which is also very important to a person's ability to balance.

Benefits

As a participant in this research study, you will experience novel types of exercise – aerobic and resistance interval training - that you may find enjoyable. You will also receive feedback on basic assessments such as body composition and cardiovascular fitness.

Risks

By taking part in this study, you may experience the following risks:
Testing Measurements: The tests that we will give all vary in difficulty level. Some may seem easy while others seem difficult. Each test will have a practice trial before you perform the task. You may discover that you do not do as well as you expect. Some test designs have a low success rate. If all the tests were easy in nature, everyone would score a 100% not allowing researchers to understand the differences in individuals. You may experience falls, fatigue, frustration, or boredom. If you experience these symptoms or any other discomfort, tell the research staff. We ask that you try your best on these tasks. If any test causes you discomfort in particular and you wish to skip it, we can do so and move on to the next test.

Exercise Session: This study includes risks that are common with participation in exercise. Since you answered "No" to the questions on the Physical Activity Readiness Questionnaire, you are at minimal risk, healthy and ready for exercise. The following discomforts may occur: light-headedness, dizziness, and possibly localized muscle pain or cramping in your leg muscles with soreness persisting for a day or two. Other risks of exercise, that are unlikely, include abnormal blood pressure, fainting, disorders of the heartbeat, and in very rare instances, heart attack. The research staff has extensive training to monitor your safety during the exercise sessions by monitoring your heart rate and subjective rating of exertion. In addition, all research staff are CPR, AED, and first aid certified.

There may be more risks unknown to the researchers.

Study Costs

Participation in this study will be of no cost to you.

Compensation

You will not be paid for taking part in this study.

Research Related Injuries

If this research related activity results in an injury, treatment will be available including first aid, emergency treatment, and follow-up care as needed. Billing for care occurs in the ordinary manner to you or your insurance company. Wayne State University does not provide reimbursement, compensation, or free medical care. If you think that you have suffered a research related injury, contact the PI right away at (313) 577-4246.

Confidentiality

All information collected about you during this study will be kept confidential to the extent allowed by law. You will be identified in the research records by a coded number. Information that identifies you personally will not be released without your written permission. However, the study sponsor, the Institutional Review Board (IRB) at Wayne State University, or federal agencies with appropriate regulatory oversight [e.g., Food and Drug Administration (FDA), Office for Human Research Protections (OHRP), Office of Civil Rights (OCR), etc.) may review your records.

When the results of this research are published or discussed in conferences, no information will be included that would reveal your identity.

Voluntary Participation and Withdrawal

Taking part in this study is voluntary. You have the right to choose not to take part in this study. If you decide to take part in the study you can later change your mind and withdraw from the study at any point. You are free to only answer questions that you want to answer. Your decisions will not change any present or future standing, grading, or participation with Wayne State University or its affiliates, or other services you are entitled to receive.

The PI may stop your participation in this study without your consent. The PI will decide and let you know if it is not possible for you to continue. The decision made is to protect your health and safety, or because you did not follow the instructions to take part in the study.

Questions

If you have any questions about this study now or in the future, you may contact Bradley Kendall or one of the research team members at the following phone number (313) 577-4246. If you have questions or concerns about your rights as a research participant, the Chair of the Institutional Review Board can be contacted at (313) 577-1628. If you are unable to contact the research staff, or if you want to talk to someone other than the research staff, you may also call (313) 577-1628 to ask questions or voice concerns or complaints.

Consent to Participate in a Research Study

To voluntarily agree to take part in this study, you must sign on the line below. If you choose to take part in this study you may withdraw at any time. You are not giving up any of your legal rights by signing this form. Your signature below indicates that you have read, or had read to you, this entire consent form, including the risks and benefits, and have had all of your questions answered. You will be given a copy of this consent form.

Signature of participant / Legally authorized representative* — Date

Printed name of participant / Legally authorized representative* — Time

Signature of witness** — Date

Printed of witness** — Time

Signature of person obtaining consent — Date

Printed name of person obtaining consent — Time

APPROVAL PERIOD OCT 26 2017 OCT 25 2018 WAYNE STATE UNIVERSITY INSTITUTIONAL REVIEW BOARD

APPENDIX C: PAR-Q AND YOU

APPROVED

OCT 26 2017

WAYNE STATE UNIVERSITY
INSTITUTIONAL REVIEW BOARD

Physical Activity Readiness
Questionnaire - PAR-Q
(revised 2002)

PAR-Q & YOU

(A Questionnaire for People Aged 15 to 69)

Regular physical activity is fun and healthy, and increasingly more people are starting to become more active every day. Being more active is very safe for most people. However, some people should check with their doctor before they start becoming much more physically active.

If you are planning to become much more physically active than you are now, start by answering the seven questions in the box below. If you are between the ages of 15 and 69, the PAR-Q will tell you if you should check with your doctor before you start. If you are over 69 years of age, and you are not used to being very active, check with your doctor.

Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly: check YES or NO.

YES	NO		
☐	☐	1.	**Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?**
☐	☐	2.	**Do you feel pain in your chest when you do physical activity?**
☐	☐	3.	**In the past month, have you had chest pain when you were not doing physical activity?**
☐	☐	4.	**Do you lose your balance because of dizziness or do you ever lose consciousness?**
☐	☐	5.	**Do you have a bone or joint problem (for example, back, knee or hip) that could be made worse by a change in your physical activity?**
☐	☐	6.	**Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?**
☐	☐	7.	**Do you know of any other reason why you should not do physical activity?**

If you answered

YES to one or more questions

Talk with your doctor by phone or in person BEFORE you start becoming much more physically active or BEFORE you have a fitness appraisal. Tell your doctor about the PAR-Q and which questions you answered YES.

- You may be able to do any activity you want — as long as you start slowly and build up gradually. Or, you may need to restrict your activities to those which are safe for you. Talk with your doctor about the kinds of activities you wish to participate in and follow his/her advice.
- Find out which community programs are safe and helpful for you.

NO to all questions

If you answered NO honestly to all PAR-Q questions, you can be reasonably sure that you can:

- start becoming much more physically active – begin slowly and build up gradually. This is the safest and easiest way to go.
- take part in a fitness appraisal – this is an excellent way to determine your basic fitness so that you can plan the best way for you to live actively. It is also highly recommended that you have your blood pressure evaluated. If your reading is over 144/94, talk with your doctor before you start becoming much more physically active.

DELAY BECOMING MUCH MORE ACTIVE:

- if you are not feeling well because of a temporary illness such as a cold or a fever – wait until you feel better; or
- if you are or may be pregnant – talk to your doctor before you start becoming more active.

PLEASE NOTE: If your health changes so that you then answer YES to any of the above questions, tell your fitness or health professional. Ask whether you should change your physical activity plan.

Informed Use of the PAR-Q: The Canadian Society for Exercise Physiology, Health Canada, and their agents assume no liability for persons who undertake physical activity, and if in doubt after completing this questionnaire, consult your doctor prior to physical activity.

No changes permitted. You are encouraged to photocopy the PAR-Q but only if you use the entire form.

NOTE: If the PAR-Q is being given to a person before he or she participates in a physical activity program or a fitness appraisal, this section may be used for legal or administrative purposes.

"I have read, understood and completed this questionnaire. Any questions I had were answered to my full satisfaction."

NAME ______________________________

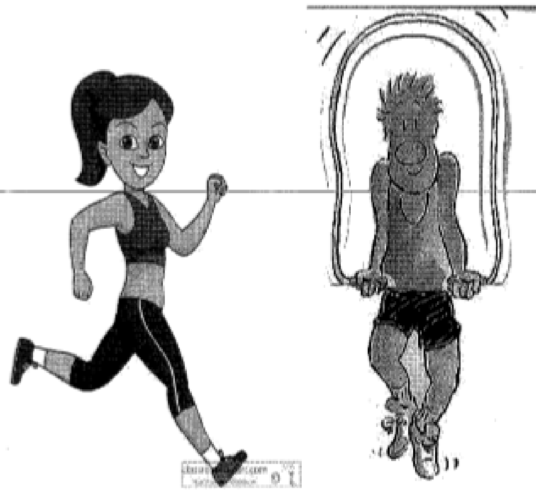
SIGNATURE ______________________________ DATE ______________________

SIGNATURE OF PARENT ______________________________ WITNESS ______________________
or GUARDIAN (for participants under the age of majority)

Note: This physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if your condition changes so that you would answer YES to any of the seven questions.

continued on other side...

APPENDIX D: RECRUITMENT FLYER



Recruiting students to assess the benefits of interval-based exercise!

RECRUITING FOR:

- Men and women
- Ages 18-40 years
- Able to complete all physical and mental assessments
- Good or corrected vision
- Free of any learning or mental disabilities

ACUTE EXERCISE RESEARCH STUDY

Researchers at the Kinesiology, Health and Sport Studies Department are recruiting students for an acute exercise research study!

As part of the study, you will complete:

- Baseline testing appointment
- Exercise sessions – consisting of aerobic interval-based and resistance interval-based exercise
- Tests of balance and reaction time

Contact Us:

Motor Behavior Research Lab

APPROVAL PERIOD

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ABSTRACT

THE EFFECTS OF ACUTE EXERCISE ON POSTURAL CONTROL, INFORMATION PROCESSING, MOTOR SKILL ACQUISITION, AND EXECUTIVE FUNCTION

by

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Advisor: Dr. Qin Lai

Major: Exercise and Sport Science

Degree: Doctor of Philosophy

Purpose

The purpose of this dissertation was to investigate the effects of acute high intensity interval training (HIIT) on postural control, information processing, motor skill acquisition, and executive function in healthy young adults. A second purpose was to compare an aerobic exercise HIIT protocol to a combined aerobic-resistance exercise HIIT protocol on cognitive function and motor abilities.

Methods

Participants (N = 60) took part in two testing sessions. The first visit served as a baseline to measure postural control (under static and dynamic settings), information processing speed, motor skill acquisition, and executive function. Participants were then randomized to either the control group, an aerobic only HIIT group (HIIT-A), or an aerobic/resistance HIIT group (HIIT-AR). During the second visit, participants performed

either 20 minutes of exercise or rested for 20 minutes and then completed the motor and cognitive tasks.

Results

No significant differences were observed between the groups on center of gravity (COG) sway during the unilateral stance test (UST) or the tandem walk test (TWT) ($p >$ .05). For information processing speed when controlling for cardiovascular fitness (CF), the HIIT-A group (M = 219.8, SE = 6.5) and the HIIT-AR group (M = 217.2, SE = 5.8) had significantly faster reaction times (mRTs) than the control group (M = 248.1, SE = 8.1). Furthermore, the HIIT-A (M = 172.1, SE = 4.6) and HIIT-AR exercise groups (M = 171.3, SE = 4.8) had significantly faster premotor times (mPMTs) compared to the control group (M = 189.7, SE = 5.7). There were no significant differences between the exercise groups. For the motor skill acquisition task when controlling for CF, there was no difference between the groups for total performance error (E) for the baseline block. Following exercise, the HIIT-A group had significantly lower E on acquisition blocks 1-3 ($p < .05$). For acquisition blocks 4-5, no differences were observed between the groups. For the executive function task when controlling for CF, during single task trials the HIIT-A group (M = 582, SE = 27) had significantly faster RTs than the control group (M = 708, SE = 25) at posttest. No differences were reported between the HIIT-A and HIIT-AR group (M = 633, SE = 22). No differences were observed for overall accuracy on single task trials between the groups ($p > .05$). For the dual-task trials, there were no differences between the groups on RT ($p > .05$). For accuracy, the HIIT-A group (M = .981, SE = .01) and HIIT-AR group (M = .970, SE = .01) had significantly fewer incorrect responses compared to the control group (M = .940, SE = .01). Again, no significant difference between the exercise groups.

Conclusion

Findings from the study support the hypotheses that acute HIIT can elicit significant improvements on information processing speed, motor skill acquisition, and executive function. This study did not support the hypothesis that acute HIIT would improve postural control. Overall, the results from this study suggest that a short bout of HIIT utilizing bodyweight exercises may have important implications on cognitive abilities and motor functions. Acute HIIT exercise appears to be a sufficient form of movement-based priming with important rehabilitation implications. Additionally, the format of the exercise protocol used in this study may be more feasible for larger groups or settings with limited exercise equipment. Research should continue to investigate this form of HIIT as well as others in populations that would benefit from improved rehabilitation and motor learning strategies.

AUTOBIOGRAPHICAL STATEMENT

Bradley Kendall graduated from Bethel College with a Bachelor of Arts degree in Exercise Science (Summa Cum Laude). He then earned a Master of Science degree in Exercise and Sports Medicine: Exercise Physiology from Western Michigan University (Summa Cum Laude), and will complete his Ph.D. (Summa Cum Laude) in May 2018 from Wayne State University in Exercise and Sport Science with concentrations in neuroscience and statistics. Bradley is also a Certified Strength and Conditioning Specialist through the National Strength and Conditioning Association.

During his time at Western Michigan and Wayne State University, Bradley has held both teaching and research assistantships, and has had the opportunity to teach classes on health education, fitness assessment and prescription, and exercise physiology. He has presented his research at national conferences and published in peer-reviewed journals. During his graduate studies, Bradley received the Outstanding Student Trainee Award in Evidence-Based Behavioral Medicine, the Outstanding Graduate Presentation Award, and a Pre-Doctoral Training Fellowship from the Institute of Gerontology at Wayne State University.

Bradley accepted a tenure-track position at Taylor University which will begin in August 2018. There, he will serve as assistant professor in the Kinesiology division and will teach courses related to research methods, motor learning, and exercise physiology. He will also continue to develop his research interests and will mentor undergraduate students in his lab. In his free time, Bradley enjoys spending time with his wife, Allie, and son, Ezekiel (aka Zeke). He also enjoys weight lifting, camping, and spending time with family and friends.