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Differential Intensities of Aerobic Exercise and Subsequent Working Memory Performance

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Abstract

Engagement in physical activity or exercise is beneficial for many different aspects of health. Cognitive health is one area in particular that has shown considerable benefits from exercise. Acute exercise paradigms have more recently been used and found to provide immediate enhancements to higher-level cognition, such as executive function and working memory. The goal of the current study was to understand how different intensities of aerobic exercise cycling influence post working memory performance and to see if the effects differ depending on whether working memory is measured immediately following exercise or after a 15 minute delay. A total of 120 participants were randomly assigned to one of four exercise intensity conditions, low, moderate, high or a resting control. Participants’ working memory was assessed at their first baseline session. During the second session, participants cycled or rested for 30 minutes and working memory was assessed immediately following and 15 minutes following the exercise or rest period. Results showed that working memory scores increased over time regardless of the condition. Further analysis also showed that working memory scores were higher following a 15 minute delay for both the low and moderate exercise conditions and there was a trend towards higher working memory scores immediately following exercise for the high intensity condition. Taken together, these results highlight the complex nature of the relationship between acute exercise and cognition.
Differential Intensities of Aerobic Exercise and Subsequent Working Memory Performance

Exercise has consistently demonstrated benefits to physical, psychological and cognitive health dimensions (Deslandes et al., 2009; Hillman, Erickson & Kramer, 2008; Warburton, Nicol & Bredin, 2006). Early recommendations provided by the U. S. Department of Health and Human Services (DHHS) suggested that higher levels of physical activity reduce the risk of many different chronic diseases including heart disease, cancer, obesity and diabetes (DHHS, 1996). Longitudinal data since then have also confirmed the health risks of a sedentary lifestyle (Warburton et al., 2006). Physically inactive women who engaged in less than 60 minutes of exercise per week experienced a 52% increase in all-cause mortality risk, 29% increase in cancer-related mortality risk and 50% increase in cardiovascular-related mortality (Hu, Willett, Li, Stampfer, & Colditz, 2004). Additionally, the level of physical fitness also seems to be important. High-fitness individuals and those who increase their fitness levels are associated with a reduction in overall premature death risk (Erikssen, 2001). A more recent report generated by the DHHS (2008) provides even more support for the substantial health benefits of engaging in physical activity. Those include a lower risk of early death, coronary heart disease, stroke, high blood pressure, type 2 diabetes, metabolic syndrome, colon cancer and breast cancer. Additionally, engagement in consistent physical activity can improve cardio-respiratory and muscular fitness, reduce depression and result in better cognitive function (DHHS, 2008). While research consistently demonstrates the physical health benefits, there is also a large amount of research suggesting the mental health benefits of regular exercise or physical activity (Deslandes et al., 2009; Paluska & Schwenk, 2000; Taylor, Sallis, & Needle, 1989).
Psychological health benefits of exercise and physical activity

Psychological disorders are extremely prevalent and it is estimated that one in four adults experiences a mental illness in any given year (Kessler et al., 2005). With such a high prevalence and the extreme costs of traditional mental health care, a large body of research has been devoted to finding effective, non-medicinal treatments for various psychological disorders. Exercise in particular has shown promise in reducing symptoms for many types of psychological disorders (Callaghan, 2004; Peluso & de Andrade, 2005). Anxiety and depressive disorders tend to experience the greatest benefits from both long term (chronic) and single bouts (acute) of exercise (Paluska & Schwenk, 2000; Petruzzello, Landers, Hatfield, Kubitz, & Salazar, 1991; Salmon, 2001; Taylor et al., 1989). Taylor et al. (1989) looked at a variety of psychiatric disorders and showed physical exercise was most effective in reducing mild to moderate depression. Similarly, Paluska and Schwenk (2000) conducted a review on the effects of exercise on depression and anxiety, examining studies that used both clinical and non-clinical populations. They found both acute and chronic aerobic exercise programs to be effective in reducing anxiety and depressive symptoms among both populations and that it was most effective when paired with typical pharmacotherapy. Other disorders such as schizophrenia have also shown benefits in response to mild or moderate physical activity. These benefits were evidenced by a reduction in both positive and negative symptoms among those diagnosed with schizophrenia (Bredin, Warburton & Lang, 2013). While the causes of schizophrenia are still not completely understood, it is believed that structural brain abnormalities and faulty neurotransmitter systems may play a large role in the development of schizophrenia. Thus, it has been suggested that the benefits of physical activity for different psychological disorders may be the result of exercise-induced physiological changes on the brain (Falkai et al., 2013).
Cognitive health benefits of exercise and physical activity

Over the last 40 years, research has accumulated suggesting that exercise plays a major role in enhancing different aspects of cognition as well as protecting against cognitive decline (Cotman & Berchtold, 2002; Guiney & Machado, 2013; Hillman, et al., 2008; Kramer, Erickson & Colcombe, 2006). Traditionally, researchers have approached the question of how exercise influences cognition by employing a specific type of exercise intervention and measuring how that intervention influences cognition (Thompson et al., 2001). The two common types are acute and chronic interventions (Roig, Nordbrandt, Geertsen, & Nielsen, 2013). Acute exercise refers to a single bout of exercise and chronic or long-term exercise refers to the consistent engagement in exercise over a certain time period (Thompson et al., 2001). Exercise researchers interested in understanding the relationship between exercise and cognition typically have individuals engage in a single bout of exercise or multiple bouts of exercise to see how the exercise influences cognition. The two strategies have been shown to exert distinct effects on cognition. Long-term interventions tend to induce more long-lasting changes on the brain and cognition, whereas acute exercise interventions may exert only transient influences on cognition (Roig et al., 2013).

Some of the strongest support for the positive influence of exercise for cognition has come from experimental and correlational chronic exercise studies examining how exercise influences different aspects of brain function and structure in older adults (Cotman & Berchtold, 2002; Erickson, et al., 2011; Guiney & Machado, 2013; Kramer et al., 2006). When compared to unfit individuals, older, high fit individuals tend to have greater gray matter density in the frontal, temporal and parietal cortices, less age-related degeneration in the prefrontal cortex, greater hippocampal volume and greater brain activation during cognitive tasks (Hillman et al., 2008; Kramer et al., 2006). Additional research has also suggested that engagement in long-term
aerobic training can reverse some age-related brain atrophy. Magnetic resonance imaging (MRI) scans were taken before and after a 6-month aerobic training program for older sedentary adults (Colcombe et al., 2006). The results showed that aerobic exercise led to an increase in gray and white matter volume in both the frontal and temporal lobes of the brain, areas thought to be heavily involved in executive function. Similarly, Erickson et al. (2011) found that compared to stretching-only controls, moderate aerobic walking for one year increased anterior hippocampal volume by 2% and improved performance on spatial memory tasks. The hippocampus is a brain structure widely believed to play an important role in memory and consolidation as well as spatial navigation. Older adults have also shown some of the greatest exercise induced improvements in cognitive abilities related to executive function (Guiney & Machado, 2013; Kramer et al., 2006). Colcombe and Kramer (2003) found that executive control processes such as planning, working memory, and inhibitory processes tend to show the greatest benefit from exercise for older sedentary adults, with moderate to large increases in performance following exercise training programs. Even single bouts of resistance exercise have been shown to drastically enhance executive function for older adults (Chang & Etnier, 2009). Taken together, these results suggest engagement in exercise as well as fitness level exert a beneficial influence on brain health, which may in turn influence cognition for older adults.

Chronic exercise has also been shown to act as a neuroprotective factor in reducing age-related cognitive decline associated with different neurodegenerative diseases, such as Alzheimer’s disease, the most common form of dementia, as well as the deficits associated with menopause (Cotman & Berchtold, 2002; Hötting & Röder, 2013; Kramer, et al., 2006). A recent review examining the effects of physical activity on cognition concluded that being more physically active early in life is associated with preserved cognitive abilities later in life and a
reduced risk for dementia (Hötting & Röder, 2013). Additionally, aerobic exercise of at least moderate intensity was found to significantly reduce the risk of Alzheimer’s disease (Loprinzi, Herod, Cardinal, & Noakes, 2013). While many factors likely play a role in the development of Alzheimer’s disease among older adults, chronic physical activity is one factor that seems to be particularly important in preserving cognitive function. Overall, these findings suggest that chronic exercise is important for brain health and cognition for older adults.

Additionally, the benefits of chronic exercise have also been evidenced in younger populations, including school-aged children, preadolescents and young adults (Chen, Fox, Ku, & Taun, 2013; Guiney & Machado, 2013; Hillman et al., 2008). Several large-scale studies have been conducted on the effects of physical education classes on academic performance among school-aged children and preadolescents with the overall finding that fitness level and participation in exercise are important predictors of academic achievement (Chen et al., 2013; Sibley & Etnier, 2003). The immediate effects from a single bout of exercise have also been shown to help improve attentional performance among adolescents as well as verbal learning and long term memory (Buddhe et al., 2012; Etnier, Labban, Piepmeier, Davis, & Henning, 2014).

Among young-adult populations, chronic aerobic exercise training has been found to increase multiple aspects of cognition, with the greatest benefits seen in executive function abilities and visuospatial memory (Stroth, Hill, Spitzer & Reinhardt, 2009). Additionally, young aerobically fit individuals tend to perform better overall on cognitive assessments compared to their unfit counterparts (Stroth et al., 2009). However, some of the research on chronic exercise and cognition among young adults has failed to find any effect (Etnier, Norwell, Landers & Sibley, 2006). Moreover, the effects of most of these studies have tended to be quite small. These results have been explained in terms of the peak cognitive abilities associated with young
adolescence. During this time, cognitive function is at its highest and thus there may be little room for exercise to improve cognition (Etnier et al., 2006).

**Acute exercise effects on cognition**

The majority of research investigating the role of exercise for cognition among young adults has tended to utilize an acute exercise strategy in order to understand the relationship (Chang, Labban, Gapin & Etnier, 2012; Tomporowski, 2003). Various explanations have been suggested to explain how a single bout of exercise can lead to enhancements in cognition. Many of those involve the physiological changes that exercise induces such as increased heart rate, increased blood flow, and an increase in neurochemicals such as catecholamines and neurotrophic growth factors (BDNF). These physiological changes may provide immediate benefits to cognition by raising arousal levels that help focus attention during cognitive task performance as well as induce changes in the brain that promote synaptic plasticity for learning and memory (Davenport, Hogan, Eskes, Longman, & Poulin, 2012; Griffin et al., 2011; McMorris, Collard, Corbett, Dicks, & Swain, 2008).

Acute bouts of exercise generally have been found to benefit various aspects of cognition. Moderate intensity exercise is most commonly found to be beneficial for cognitive measures of reaction time, attention and more recently various executive control functions (Coles & Tomporowski, 2008; Davranche & McMorris, 2009; Lambourne, 2012; Martins, Kavussanu, Willoughby & Ring, 2013). Despite the overwhelming support for the idea that even a single bout of exercise can benefit cognition, some discrepancies exist regarding exactly what types of cognition are enhanced from a single bout of exercise and what exercise parameters induce the benefits for cognition (Brisswalter, Collardeau & Rene, 2002; McMorris, Sproule, Turner & Hale, 2011; Tomporowski & Ellis, 1986). Some researchers have found that single bouts of
exercise enhance different aspects of cognition, while others have found no effects or detrimental effects on cognition (McMorris & Hale, 2012; Tomporowski, 2003). Many of the discrepancies are likely a result of the variability in methodological variables such as exercise intensity, exercise duration, type of cognitive task, time when cognition is tested, and the baseline fitness level of individuals (Brisswalter, Collardeau & Rene, 2002). Thus, it is important to gain a full understanding of how acute exercise influences cognition by taking into account how the variation in methodological variables likely influence how a single bout of exercise influences cognition.

**Early research on acute exercise and cognition**

Early research examining the relationship between acute exercise and cognition was plagued with multiple problems. One of the primary issues was the excessive use of cognitive tasks that assessed processing speed, such as reaction time measures (Brisswalter, Arcelin, Audiffren & Delignieres, 1997; Collardeau, Brisswalter, & Audiffren, 2001; Fery, Ferry, Vom Hofe, & Rieu, 1997; Hogervorst, Riedel, Jeukendrup, & Jolles, 1996). The most common measures were simple reaction time (SRT) and choice reaction time (CRT) tasks. These tasks require the individual to respond to a stimulus immediately upon appearance or to make a choice among multiple stimuli as fast as possible. While reaction time measures of cognition are important indices of processing speed, other aspects of cognition are equally important to understand and unfortunately were not examined during this early period of research.

Another issue with this early research was the emphasis on high-intensity, exhaustive exercise and its effect on cognition. This stemmed from a belief in the resilience and endurance of the human body as well as a curiosity to understand the limits of our capacity (Brisswalter et al., 2002). As a result, much of this research focused on how extreme exercise protocols
influenced concurrent reaction time performance (Brisswalter et al., 1997; Collardeau et al., 2001; Fery et al., 1997). Similarly, most of the individuals recruited for these studies tended to be high-fit, male individuals or athletes (Collardeau et al., 2001; Fery et al., 1997; Hogervorst et al., 1996) with females and those of a lower fitness being neglected. Moreover, the findings of these studies tended to be discrepant, with some finding benefits from exercise while others found detriments. The small sample sizes of this early research might have contributed to this, increasing the occurrence of Type II errors.

A final problem with this early research was the variation in exercise procedures, which made it difficult to compare studies. Some varied the intensity throughout the exercise (Brisswalter et al., 1997; Hogervorst et al., 1996; Paas & Adam, 1991), while others used consistent intensity throughout (McMorris & Keen, 1994). Some used longer exercise durations (Collardeau et al., 2001), whereas others studies used shorter (McMorris & Keen, 1994). Finally, some were simply hard to quantify because the researchers omitted important details regarding the exercise procedures (Hogervorst et al., 1996) as well as used unique exercise methods (Collardeau et al., 2001). Adding to this, many of these studies tested reaction time at various times throughout the exercise making it difficult to deduce any firm conclusions on the relationship between acute exercise and cognition.

Reviews of the literature published before 2000 also concluded that clear support for the beneficial effects of acute exercise on cognition could not be determined due to multiple methodological problems in the design and execution of these studies (Etnier et al., 1997; Tomporowski & Ellis, 1986). They also pointed out some of these major flaws hampering the understanding of how acute exercise influences cognition and provided direction for future researchers. This led researchers to address some of these gaps and pursue new avenues in order
to gain a better understanding of how acute exercise influences various aspects of cognition. New research began to emerge that examined how exercise influenced other types of cognition, such as memory and executive function, employed exercise procedures in controlled lab settings, expanded participant pools to include individuals of average fitness levels to make findings more generalizable to the public, and examined how moderate to low intensities of exercise influence cognition.

The goal of the current study was to further expand this field by examining how various intensities of aerobic exercise cycling influence subsequent executive function, specifically, testing working memory, immediately following an exercise bout and following a short delay. Researchers have determined that a single bout of moderate exercise is beneficial for higher order cognition (Martins, et al., 2013), but have neglected how other intensities, low and high, influence working memory. In addition, the time course effects of exercise following exercise cessation on working memory have not been determined (Joyce, Graydon, McMorris & Davranche, 2009). It remains to be seen if the time course effects for lower intensity aerobic exercise are shorter compared to the time course effects of high intensity exercise. It may be that low intensity exercise is most facilitating immediately following exercise, whereas higher intensity exercise is most facilitating following a short delay. Understanding the immediate effects of various intensities of exercise on cognition may provide further information on how the accumulation of those immediate effects contributes to the conditioning effects of chronic exercise and how that in turn leads to better cognitive health outcomes. It is important to gain a full understanding of both in order to truly understand the beneficial effects of physical activity.
Theoretical perspectives

A major theoretical framework used to describe how acute exercise may affect cognition is the inverted-U hypothesis of arousal (Yerkes & Dodson, 1908). The seminal work of Yerkes and Dodson examined the relationship between arousal and performance. They proposed that this relationship followed an inverted U pattern, in that as the level of arousal increases performance also increases, but beyond a certain point performance begins to decline when arousal levels are too high. This theory suggests that an optimal level of arousal is required for peak performance and arousal levels that are either too high or too low result in decreased performance. One way to increase arousal is through physical activity, with higher intensities of exercise inducing higher arousal levels. Based on this theory, both high and low intensity exercise should result in sub-optimal cognitive task performance and intermediate intensity exercise should result in peak cognitive performance. Similarly, the cue utilization theory posited by Easterbrook (1959) suggests a positive relationship between arousal level and attention. An elevated level of arousal is necessary for focused attention to a task, called narrowing of attention. However, if arousal continues to increase, attention continues to narrow and cues relevant to the task become obscured resulting in diminished performance. This theory is particularly important because attention is a major determining factor for successful working memory performance, such that individuals who are better able to focus their attention tend to have much higher working memory capacities (Engle, 2002; Kane, Bleckley, Conway, & Engle, 2001). The cue-utilization theory also suggests that physical activity of moderate levels may raise arousal and attention to a level that helps facilitate performance, but physical activity of a higher intensity may raise arousal levels too high resulting in a decreased level of attention. These theories lend support to the idea that exercise-induced increases in arousal may enhance
cognitive performance, but exercise of an intensity that exceeds the optimum threshold of arousal may interfere with attention and focus, leading to decrements in cognition.

A more recent theoretical framework that has been suggested to explain the relationship between acute exercise and higher cognitive function is the transient hypofrontality hypothesis (THT). Dietrich (2003; 2006) provides a neurocognitive theory to account for the effects of acute exercise on prefrontal-dependent cognition. He purports that resources in the brain are finite and coordinating body movement exerts a significant neural cost on the brain. Physical activity induces multiple demands on specific brain areas involved in motor, sensory and autonomic function, which in turn results in fewer available resources for other neural regions. Thus, the brain reserves its resources in order to support fundamental processes, such as movement, and down-regulates other neural structures that are not critical to this task. The particular area of the brain most affected by this process is the prefrontal cortex (PFC), which is primarily involved in complex cognition and behavior. Acute exercise is believed to induce a momentary decrease in prefrontal-mediated cognition due to the reallocation of metabolic resources to sustaining the coordination of movement. Based on this theory, we would expect higher intensity exercise to monopolize available brain resources and lead to decreased performance on higher order cognitive tasks, due to fewer resources available to support successful task performance.

Taken together these theoretical perspectives suggest that the physiological effects of exercise may directly influence areas of the brain that are important for cognition. In addition they also provide insight on how different intensities of exercise may influence more complex cognitive behavior controlled by the PFC. Specifically, exercise that raises arousal levels just enough without inducing fatigue may be optimal for successful cognitive performance.
Executive function and working memory

Research examining the relationship between acute exercise intensity and higher levels of cognition such as executive functioning has only recently been investigated (Alves et al., 2014; Del Giorno, Hall, O’Leary, Bixby, & Miller, 2010; Dietrich & Sparling, 2004; Hung, Tsai, Chen, Wang, & Chang, 2013; Lambourne, Audiffren, & Tomporowski, 2009; Tomporowski et al., 2005; Yanagisawa et al., 2010). Executive function is typically conceptualized as a meta-cognitive process that oversees and coordinates various other fundamental cognitive processes, such as mental set-shifting, inhibition and updating information in working memory (Miyake et al., 2000). These executive control processes are resource-limited, functionally distinct, and associated with conscious awareness (Hillman, Snook & Jerome, 2003). Research examining the relationship between acute exercise and different aspects of executive function has tended to focus on the inhibition and switching aspects of the executive function model (Alves et al., 2014; Lambourne et al., 2009; Tomporowski et al., 2005; Yanagisawa et al., 2010). Pontifex et al. (2009) pointed out that research is lacking in how acute bouts of exercise influence the working memory aspect.

The working memory component is separated into two subcomponents that simultaneously process and store information during higher-order cognitive tasks (Baddeley, 2010). A defining characteristic of working memory is the active manipulation of information or executive attention (Kane, Bleckley, Conway, & Engle, 2001). Executive attention represents the ability to maintain information for a certain interval of time in the presence of interference. Thus, the ability to maintain focus during situations when environmental distracters are at their highest is the prominent characteristic that defines working memory capacity (Kane & Engle, 2002). Successful working memory performance is highly dependent on the pre-frontal cortex (PFC)
and is important for many complex cognitive processes such as focused attention, language comprehension, problem solving, reasoning ability, and attentional control (Baddeley, 2012; Daneman & Carpenter, 1980; Kane et al., 2001). The small number of studies conducted to understand how acute exercise influences working memory have been discrepant, with some researchers showing enhancements to working memory, while others showed decrements (McMorris et al., 2011). Thus, given recent proposed theories suggesting that exercise inhibits the PFC (Transient Hypofrontality Theory) and the major role the PFC plays in successful working memory performance, it is important to address these discrepancies in the literature using this framework to determine if acute bouts of exercise are beneficial or detrimental for working memory aspects of executive function.

**Acute exercise effects on executive function**

Research examining how a single bout of exercise influences various aspects of executive function have suggested that moderate intensity exercise is beneficial when executive function is measured following exercise (Audiffren, Tomporowski, & Zagrodnik, 2009; Tomporowski et al., 2005; Yanagisawa et al., 2010). Tomporowski et al. (2005) found that performance on a modified version of the Paced Auditory Serial Addition Task (PASAT) was enhanced immediately and 30 minutes following a 40-minute bout of moderate intensity cycling compared to baseline performance on the PASAT. The PASAT measures the rate and capacity of auditory information processing as well as sustained and divided attention. Similarly, participants who completed a moderate bout of aerobic exercise cycling showed increased performance on the Tower of London task (TOL), which specifically measures the planning aspect of executive function (Hung, Tsai, Chen, Wang, & Chang, 2013). Participants who exercised showed lower total move scores and greater total correct move scores compared to those who did not exercise.
These results highlight the beneficial effects that a moderate bout of exercise has on executive function measured after exercise. However, questions remain regarding how long the benefits to executive function last following a bout of moderate exercise.

Studies where exercise and executive task performance occur simultaneously have tended to shown decrements for cognition (Alves et al., 2014; Dietrich & Sparling, 2004; Griffin et al., 2011; Lambourne, et al., 2009; Wang, Chu, Chu, Chan, & Chang, 2013). Dietrich and Sparling (2004) were among the first to examine performance on a complex cognitive task during exercise. Participants cycled or ran at a high intensity while completing the Wisconsin Card Sorting Task (WCST) and an intelligence test. The WCST is a common neurropsychological test used to measure prefrontal lobe function (Etnier & Chang, 2009). They found that the exercise had no effect on the test of general intelligence but both running and cycling resulted in more errors on the WCST. Similarly, Alves et al. (2014) wanted to understand how high intensity interval training (HIIT) influenced concurrent executive function and short-term memory. HIIT is a type of exercise characterized by intermittent periods of high intensity exercise and periods of low intensity or recovery exercise (Alves et al., 2014). This type of exercise has recently been proposed as a more time-efficient cardiovascular exercise compared to more traditional types (Gibala, Little, Macdonald, & Hawley, 2012). The researchers found the HIIT session resulted in reduced performance on the Stroop task, commonly thought to measure selective attention and cognitive flexibility (Banich et al., 2001). Both of the studies described above used higher intensity exercise protocols and thus more research is needed that examines how low intensity exercise influence executive function.

Additionally, recent research has been conducted examining how executive function is influenced by different exercise intensities. Labelle, Bosquet, Mekary and Bhrer (2013)
conducted a study examining the effect of different aerobic exercise intensities on concurrent measures of executive function. Participants cycled for seven minutes at a low, moderate or a high intensity while completing the Stroop task. Their results revealed that higher-intensity exercise led to decreased performance on the Stroop measure whereas lower and moderate intensity exercise had no effect on simultaneous Stroop task performance. These results suggest that even short amount of high intensity exercise can be detrimental to simultaneous executive function, however it remains to be determined if longer bouts of low intensity exercise still exert no influence on executive function. Similarly, Wang et al. (2013) wanted to understand how executive functions are affected during acute exercise and whether exercise intensity plays a role. Participants exercised at either a low, moderate or high intensity while also completing the Wisconsin Card Sorting Task (WCST). Their results showed that participants in the high intensity group demonstrated the lowest conceptual level responses and number of categories completed and highest perseverative responses on the WCST compared to the other exercise intensity groups. While the low and moderate groups showed no impairment on this task during exercise. These results seem to suggest that high intensity acute exercise is detrimental to executive function both during and immediately following exercise. However, it remains to be determined if the negative effects from high intensity exercise on executive function persist once exercise ceases.

**Acute exercise effects on working memory**

Recently researchers have switched their attention to trying to understand how different levels of acute exercise influence aspects of working memory. Martins et al. (2013) examined how general executive function and working memory performance are influenced by shorter and lower intensities of acute exercise. They measured participants’ performance on the PASAT and
Sternberg task while the participant exercised at a low to moderate intensity. The Sternberg task of working memory primarily taps processing speed, selective attention and inhibition abilities. Their results showed that brief low to moderate exercise intensity was beneficial for both the PASAT and Sternberg task performance. Specifically, correct responses increased for the PASAT and response latencies decreased for the Sternberg task when compared to baseline measures. The results from this study are particularly important because they suggest that lower intensity bouts of exercise might be better for working memory performance. However, this study assessed task performance during exercise and thus it is not clear whether these results would hold true if participants were tested following the exercise.

Soga, Shishido and Nagatomi, (2015) conducted two separate studies to understand how different levels of moderate intensity exercise (60% and 70% of maximum heart rate) influence inhibitory control and working memory both during and five minutes following exercise among adolescents. The tasks they used to measure these different aspects of executive function were the flanker task (inhibitory control) and a modified version of the n-back task (working memory). They found no change in performance on the flanker task during or after both levels of moderate exercise when compared to baseline. However, when participants’ working memory was tested during exercise, both levels of moderate intensity exercise led to an increase in reaction time whereas accuracy only diminished when participants exercised at 70% of their maximum heart rate but not when exercising at 60%. Finally, they did not find any difference in n-back task performance five minutes following moderate exercise when compared to baseline. Overall, the results of this study suggest that moderate exercise may exert a negative influence on working memory when the two activities occur simultaneously. Interestingly, these authors did not find an effect on working memory five minutes following exercise. However, it may be
that a longer recovery period is necessary in order to positively influence working memory. It should also be noted that this study was conducted with adolescents between the ages of 15 and 16 years of age. It is unclear whether or not these results would persist if this study were replicated with a young adult sample.

Only a handful of studies have directly tested how a single bout of exercise influences working memory performance following a single bout of aerobic exercise. Pontifex, Hillman, Fernhall, Thompson, and Valentini (2009) examined the effects of moderate aerobic and resistance exercise on Sternberg working memory performance, both during and 30 minutes following exercise. Their results showed no effect of resistance exercise on working memory performance. However, following 30 minutes of moderate aerobic exercise, reaction time latency was faster when compared to baseline but no change in accuracy on the Sternberg task was found. These results are also in line with Sibley and Beilock (2007), who looked at the relationship between working memory capacity (WMC) and acute moderate exercise. They had individuals of either a low or high WMC engage in a 30-minute bout of moderate self-paced exercise to see if baseline WMC played a role in the effects of a single bout of exercise on working memory. They found that low-WMC individuals showed a significant increase in working memory performance immediately following the exercise. These results suggest that individuals with lower working-memory abilities may have the most to gain from a single bout of exercise.

Finally, Buddhe et al. (2010) conducted a study among 9th grade high school students to try and better understand the role that exercise-induced hormones play in influencing auditory working memory performance. Their goal was to try and find the optimal intensity for a short exercise intervention for post-working memory performance. Participants completed the Letter
Digit Span (LDS) task before and 10-15 minutes after running 12 minutes around the track at either a moderate (50-65% of maximum heart rate) or high intensity (70-85% of maximum HR). They found that those students who exercised at a moderate intensity showed a significant increase in post working memory scores when compared to baseline working memory scores. They also found that students with a lower working memory capacity increased their working memory scores from baseline to post regardless of whether they exercised at a moderate or high intensity. These results suggest that shorter bouts of moderate intensity exercise are more beneficial to post working memory performance compared to higher intensity bouts of exercise. In addition, these results support the findings of Sibley and Beilock (2007) in that those with a lower working memory capacity have the most to gain from a bout of exercise, regardless of the intensity.

Overall, these results suggest that individuals with lower working-memory abilities may have the most to gain from a single bout of exercise. The results from these studies also suggest that working memory performance may show an immediate benefit from a moderate or low-intensity bout of exercise, and may be diminished immediately following a high-intensity bout of exercise. However, only one study was found that showed benefits immediately following lower-intensity exercise and so more research is needed to verify this.

**Time course effects following a single bout of exercise on executive function and working memory**

Few studies have been conducted to determine the time-course effect that exercise has on higher levels of cognition. A recent review of exercise and cognitive task performance revealed that very few studies have been conducted that examine how long the exercise-induced changes to cognition last (McMorris & Hale; McMorris et al., 2011). Joyce, Graydon, McMorris and
Davranche (2009) found that performance on a stop-signal task was unchanged immediately following a 30-minute bout of low intensity exercise but was increased 30 minutes following exercise cessation. Furthermore, these effects on the stop-signal task were seen up to 52 minutes following the exercise. These results suggest that exercise may induce transient physiological changes that last almost an hour after exercising. Hung et al. (2013) recently examined the immediate and delayed effects of acute exercise on the Tower of London task. Results showed improvements on the total move score immediately following exercise and better response inhibition at both 30 and 60 minutes post exercise. These results also suggest sustained effects of exercise on executive function. However, a study conducted by Lambourne, et al. (2009) found that PASAT performance was unchanged 30 minutes after a moderate bout of exercise suggesting that exercise may influence different aspects of executive function. Only one study was found that tested the delayed effects of exercise on working memory performance. Maleki, Bahram, Rajabi and Farrokhi (2013) found Stroop performance following a high intensity bout of exercise decreased during and immediately following exercise, whereas Stroop performance increased for all participants 15 minutes following either a low, moderate or high intensity bout of exercise. However, it should be noted that these researchers chose the Stroop task to measure working memory. Overall, these few results suggest that exercise-induced changes may be sustained following exercise, but more research is needed to determine the specific time-course exercise has on measures of working memory and whether the time-course of the effects vary with the intensity of exercise.

The current study sought to address gaps in this literature by examining how different intensities of aerobic exercise cycling (low, moderate, high, and a no-exercise control) influence post working memory performance. Additionally, this study examined the time-course effects of
aerobic exercise by measuring working memory immediately following and 15-minutes following exercise. The hypotheses are as follows:

**Changes in working memory scores over time for each exercise condition (Within-subjects)**

1a.) Working memory performance for the resting control condition will remain stable from baseline to immediately following and 15 minutes following rest.

1b.) Working memory performance will increase compared to baseline immediately following low intensity aerobic exercise, but return to baseline levels 15 minutes following low intensity aerobic exercise.

1c.) Working memory performance will increase compared to baseline immediately following and 15 minutes following moderate intensity aerobic exercise.

1d.) Working memory performance will decrease compared to baseline immediately following high intensity aerobic exercise but increase compared to baseline 15 minutes following high intensity aerobic exercise.

**Effects of different exercise intensities on post working memory scores (Between-subjects)**

2a.) Working memory performance immediately following exercise will be significantly lower for high intensity exercise compared to low-or moderate-intensity exercise.

2b.) Working memory performance immediately following exercise will be significantly higher for moderate-intensity exercise compared to low-or high-intensity exercise.

2c.) Working memory performance 15 minutes following exercise will be significantly higher for moderate and high-intensity exercise compared to low-intensity exercise.
Relationship between reported physical activity/sitting and baseline working memory

3a.) Individuals who report more time spent engaging in physical activity for the last seven days will have higher baseline working memory scores compared to individuals who report less time.

3b.) Individuals who report more time spent sitting for the last seven days will have lower baseline working memory scores compared to individuals who report lesser amounts of time spent sitting.

Method

Pilot study

A small pilot study was conducted in order to test and refine the methodology for the full study. The different exercise intensity conditions were tested to ensure feasibility for participants. It was also important to ensure that participants would have no problem visiting the lab for two separate sessions, as this was a two-part study.

Power Analysis

Previous research examining the relationship between different intensities of acute exercise on executive function and working memory revealed small to moderate effect sizes ranging from $d = .38 - .61$ (Lambourne & Tomporowski, 2010; McMorris et al., 2011; McMorris & Hale, 2012). Using conventional guidelines, an alpha of .05 and power of .80 were selected. A power calculation for a mixed model ANOVA for both between and within factors was conducted using G*Power Software version 3.0. Separate sample size calculations were conducted for within and between factors. The estimated sample size for testing the between subject differences was selected as this estimation was larger than the estimation for testing the
within subject differences. Based on these calculations, it was determined that a sample size of 120 participants would be needed.

**Sample**

A total of 146 participants were recruited to participate in this two-part exercise study through the human participant pool (HPP) at California State University San Marcos (CSUSM). Twelve participants were ineligible due to current health conditions, injuries preventing them from exercising, a BMI above 31 or those who reported being sedentary. Five participants VO₂ value fell outside the inclusion range for healthy, young adults (25-55ml/kg). Additionally, six participants completed their first session but failed to show up for their second session and three participants were unable to complete both exercise sessions. The final sample consisted of 120 college students between the ages of 18 - 26 (\(M=20.20, SD=1.82\)) who were enrolled in lower-division Psychology courses, with an equal number of participants in each condition. The sample was primarily female (74%) and the majority of students identified as either Caucasian (32%) or Hispanic (41%).

An extensive medical questionnaire was used to ensure that all participants included in the study were healthy enough for exercise, in accordance with the most recent recommendations provided by the American College of Sports Medicine (ACSM, 2013). All participants in the final sample met the inclusion criteria of 18-26 years of age, VO₂ max between 25-55 mL/kg per minute, not sedentary, BMI below 31, free of any known medical or health conditions and not taking any psychotropic medications that could affect cognition. Any participants who did not meet all of these criteria were told that they were not eligible to participate and were thanked for their time.
Design

All participants were required to visit the Kinesiology lab for two separate sessions, approximately one week apart. The first session was used to assess maximum oxygen uptake (VO2 max indicator), which is a widely-used exercise test used to determine aerobic fitness and was used to set the intensity of the second exercise session. During the second session, participants exercised for a total of 30 minutes at a randomly assigned intensity level (low, moderate, high or control). For each participant, the absolute level of the set workload corresponding to their condition was based on the results of their VO2 maximal test. Working memory was assessed at three different time points, prior to and at two time points following the exercise.

A 4 (exercise intensity) X 3 (time) mixed model factorial design was used for this study. The between subjects factor for this study was exercise intensity (low, moderate, high, and resting control) and the within subjects factor was time when cognition is tested (baseline, 2 minutes after exercise, and 15 fifteen minutes after exercise). Participants were randomly assigned to one of four exercise intensity conditions and working memory was tested prior to exercise (baseline), 2 minutes following the cessation of the exercise and 15 minutes following the cessation of the exercise. The dependent variable in this study was the total number of trials correct on the Letter-Number Sequencing Test (LNS).

Apparatus

*Cycle Ergometer.* The Velotron Dynafit Pro (Racermate Inc., Seattle, WA) cycle ergometer was used as the mode of exercise for this study. This is a high-precision, computer-controlled, electronic bicycle ergometer. This ergometer uses a magnetically-braked flywheel that is controlled via computer software which sets the selected exercise protocol. Ergometer
shifting is all electronically based with virtual gearing. A preset protocol is loaded onto the computer software and resistance is automatically adjusted on the ergometer, independent of cadence. Watts, cadence, heart rate, speed, distance, time and calories are displayed and recorded for instantaneous, average and peak values. Adjustments can be made to modify seat height and handle bar height to fit riders between 4’8” to 6' 10”.

**Exercise Protocols**

Participants were required to participate in two experimental sessions. The first session was used to determine their VO₂ maximal oxygen consumption (VO₂ max) and the second was the exercise intervention and cognitive measures.

*Graded VO₂ maximal oxygen consumption test.* VO₂ max or maximal oxygen consumption is a common procedure used in exercise physiology to determine aerobic fitness (ACSM, 2013). VO₂ max is believed to represent functional limitations of the cardiovascular system as well as provide a proxy measure of aerobic fitness capacity (Astorino et al., 2000). For this study, we chose to use an exercise cycle for all exercise procedures as this mode of exercise has been shown to result in fewer injuries (Millet, Vleck, & Bentley, 2009). We obtained participant age, height and weight, as this information is used in the calculation of VO₂.

Participants were instructed to pedal at a consistent pace throughout this test, maintaining a minimum pedal rate of 50 rpm. For this test, participants started off cycling at a low resistance, which increased continuously every few seconds until the individual could no longer persist. The more aerobically fit an individual is the longer he or she is able to continue to pedal against the increasing resistance. At the end of the exercise test, the researcher noted the maximum watts each participant attained. The second exercise session was based on a percentage of the
maximum watts, which reflected either a low, moderate or high intensity bout of acute exercise personalized to the participant.

To assess VO2 for each participant, a 25 or 30-watt ramp protocol was used, which lasts approximately 7 to 11 minutes (Yoon, Kravitz & Robergs, 2007) depending on the aerobic capacity of the individual. Those who reported regularly engaging in five or more days of cardiovascular exercise per week were assigned the 30-watt ramp protocol (N = 17), as this test starts at a slightly higher resistance for those individuals who may be more aerobically fit. The test starts with a two-minute, low-resistance warm-up. Following the warm-up, the wattage on the bike increases continuously every few seconds until the participant is no longer able to continue, representing volitional fatigue or their max. During the VO2 test, participants wore headgear and a nose clip and were required to breathe into a mouthpiece and hose connected to gas analyzers, which measured pulmonary gas exchange (ParvoMedics True One, Sandy, UT). A metabolic cart was used to measure respiratory airflow via a pneumotachometer. A sample line was connected to the pneumotach machine which continuously pumped air to and from the O2 and CO2 gas analyzers, which detected pressure differences to determine flow rate. Based on the results of this test, researchers were able to assign a specific intensity of exercise that was based on each individual’s maximum performance, specifically tailored to their own capabilities for exercise.

Certain conventional standards were used to ensure all participants achieved their true max, which included meeting two out of the three following criteria: 1) a plateau in VO2 with increases in bike wattage\(^1\), (2) maximal respiratory exchange ratio (RER) value > 1.10, and (3) maximal heart rate (HR) within 10 beats per minute (BPM) of the age-predicted maximum

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\(^1\) The relationship between VO2 and wattage follows a linear pattern, such that as one increases so does the other.
equation \((220 - \text{age})\). Based on these criteria it was determined that all participants achieved their true max. At no point during the VO2 test did any of the participant’s heart rate ever go more than 10 BPM above their age-predicted maximum. The VO2 max value obtained for each participant was compared to gender and age-based VO2 max normative data and only those participants whose VO2 max value fell between 25-55 mL/kg per minute were included in the current study, as these values reflect average, healthy young adults (Heyward, 2010).

**Acute exercise intervention.** In the second session, participants engaged in a single, 30-minute bout of aerobic exercise on a cycle ergometer at either a low, moderate or high intensity or they rested for entire duration. The four intensity conditions were based on the participants maximal watts attained (Wmax) on their VO2 max test, which represented a percentage of the individuals max capacity. Participants engaged in a three-minute warm-up, followed by 25 minutes at one of the assigned intensities, and a two-minute cool-down.

**Exercise conditions**

*No exercise (control):* Individuals rested for 30 minutes, seated on the cycle without any pedal movements. Participants were offered a selection of neutral magazines to read during this time.

*Low intensity exercise:* Individuals cycled for 25 minutes at 30% of their maximal watts. Participants also warmed-up and cooled-down at 30% of their maximal watts. This consisted of cycling at a constant workload for the entire 25 minutes. For example, someone who attained 200 watts on their VO2 max test in the low-intensity condition exercised at 60 watts for 25 minutes.

*Moderate intensity exercise:* Individuals cycled for 25 minutes at 50% of their maximal watts. Participants also warmed-up and cooled-down at 30% of their maximal watts. This consisted of cycling at a constant workload for the entire 25 minutes. For example, someone who attained...
200 watts on their VO2 max test in the moderate-intensity condition exercised at 100 watts for 25 minutes.

*High intensity exercise:* Individuals cycled for 25 minutes at intervals fluctuating between 80% and 30% of their maximal watts. Participants also warmed-up and cooled-down at 30% of their maximal watts. Previous research has shown that it is difficult for individuals of an average fitness to maintain high intensity exercise (> 80%) for long durations (Labelle et al., 2013). Additionally, preliminary pilot testing confirmed that it would be too difficult for our sample to cycle at 80% of their max for the entire 25 minutes. Thus, we chose to utilize an interval exercise strategy, which created a more manageable high intensity exercise condition for individuals of an average fitness. This exercise strategy was composed of alternating intervals of both high and low intensity cycling, which included 10, one-minute bouts at 80% of their maximal watts interspersed with 10, one-and-a-half minute bouts at 30% of their maximal watts. For example, someone who attained 200 watts on their VO2 max test in the high-intensity condition would alternate between 1:00 intervals at 160 watts (80%) and 1:30 at 60 watts (30%).

*Manipulation check.* Heart rate was monitored throughout the acute exercise intervention to determine whether the heart rate coincided with the assigned intensity condition. However, previous research has shown that heart rate varies greatly between individuals and even for the same individual from day-to-day (Achten & Jeukendrup, 2003). Additionally, a phenomenon known as cardiovascular drift occurs where heart rate increases over time, regardless of a change in intensity, largely due to increased body temperature (Achten & Jeukendrup, 2003). Thus, these characteristics of heart rate were taken into consideration when devising heart rate cut-offs. Participants in the low intensity exercise condition needed to have an average heart rate below 151 BPM, participants in the moderate intensity condition needed to have an average heart rate...
below 181 BPM, and participants in the high intensity condition needed to have an average heart rate above 161 BPM. All participants included in the analysis fell within the specified heart rate cut-offs for their assigned condition.

Ratings of Perceived exertion (RPE) were also collected at five time points throughout the 25-minute exercise (at 5 minutes, 10 minutes, 15 minutes, 20 minutes and 25 minutes). This scale was used to determine how participants perceived the exercise in terms of effort. Because this scale is a subjective assessment of perceived exertion, we chose not to exclude anyone based on his or her ratings. Rather the ratings were collected and used primarily as informative data.

**Measures**

*Demographics.* Demographic variables were assessed including gender, age, and ethnicity.

*Medical and Health Screening.* Participants completed a medical and health questionnaire in order to ensure that all participants were healthy enough for physical activity (ACSM, 2013). The questionnaire asked about previous cardiovascular problems such as chest pain, heart murmurs, and shortness of breath as well as other types of medical conditions such as diabetes, asthma, neurological problems and any history of psychiatric disorders. We also inquired about any cognitive impairment and excluded participants who were taking any kinds of medications. Any participant who reported a current medical or health condition was excluded from the study. Additionally, we excluded anyone with a BMI greater than 31, those who reported engaging in less than 60 minutes of low-moderate cardiovascular activity per week and any women who reported being pregnant or thought they might be pregnant. Finally, in an effort to reduce the risk of injury or cardiac event, this study was restricted to young, healthy adults between the ages of 18-26. Individuals who did not meet the inclusion/exclusion criteria for the
medical and health questionnaire were told that they were not eligible to participate and were thanked for their time.

*International Physical Activity Questionnaire (Long form).* The IPAQ-LF is a 31-item, self-report physical activity measure used in many different countries to assess physical activity in multiple domains such as leisure, domestic, employment, and transportation (Craig et al., 2003). This measure has demonstrated good test retest reliability ($r = .80$) as well as moderate criterion validity compared against accelerometer daily activity tracking ($r = .33$) (Craig et al., 2003).

This questionnaire is separated into five domain-specific subscales, including work-related physical activity (walking, moderate work activity, vigorous work activity), transportation-related physical activity (motor vehicle, walking, and bicycling) domestic-related physical activity (yard-work, house-work), leisure-time physical activity (walking, moderate leisure activity, vigorous leisure activity) and time spent sitting, which are specific to the previous seven days. The types of questions within each physical activity domain assess the type of activity (e.g. walking, cycling, gardening, etc.) the intensity of the activity (vigorous, moderate) as well as the duration and frequency of each activity (minutes and days) completed within the past seven days. Participants were asked to report on the number of days spent engaging in the activity at moderate and vigorous intensities, which range from “no engagement in the activity, 1-2 days per week, 3-4 days per week, 5-6 days per week and 7 days per week.” Participants were also asked to indicate the amount of time spent, in minutes, on the activity.

Based on the reported minutes and days spent doing moderate and vigorous activity within each domain, total minutes/week were computed for each of the physical activity domains (Work, Transportation, Domestic and Garden and Leisure). Those minutes were summed for a
score that represented the total amount of minutes spent engaging in various physical activities for the previous week (IPAQ, 2005).

*Perceived Exertion Scale.* Ratings of perceived exertion (RPE) were assessed every five minutes throughout the 25-minute bout of exercise using Borg’s Rating of Perceived Exertion (RPE) Scale. This commonly used measure assesses perception of physical exertion (Borg, 1982) and reflects how heavy and strenuous the exercise feels to the individual. This measure was used to inform the researcher on whether the participant’s perception of the exercise coincided with the actual intensity of the exercise (Dunbar et al., 1992). This measure has demonstrated good reliability (α > .90) as well as good criterion validity for predicting VO₂ performance for cycling exercise (r = 0.83) (Chen, Fan, & Moe, 2002). The scale ranges numerically from 6-20 with descriptors provided for odd numbers as well as the first and last numbers of the scale. For example, values from 6-11 range from “no exertion to light exertion”, values 12-14 represent “some exertion”, and values from 15-19 range from “hard to extremely hard exertion”. A rating of 20 on this scale represents “maximal exertion.” The range of this scale can also be used as a proxy to predict heart rate as research has shown strong convergent validity between ratings of perceived exertions and actual heart rate (Chen et al., 2002). Participants were provided with the following instructions, “Throughout the exercise, I will be asking you to rate how hard you feel you are working using this scale, which ranges from 6-20, with 6 representing 0 exertion and 20 representing maximal exertion. This feeling should reflect how heavy and strenuous the exercise feels to you, combining all sensations and feelings of physical stress, effort, and fatigue. Do not concern yourself with any one factor such as leg pain or shortness of breath, but try to focus on your total feeling of exertion. You will choose the number that best describes your current level of exertion, as honestly as possible, without thinking about the actual physical load.”
Working memory test. The working memory test used in this study was the letter–number sequencing test (LNST). This is one of the subtests of the Wechsler Intelligence Test (Wechsler, 1997), which measures verbal working memory and specific abilities related to visuospatial manipulation, attention and processing speed. The test-retest reliability for the original standardized sample of adults over a two to twelve week period demonstrated acceptable reliability of .70 (Wechsler, 1997), with recent researchers utilizing alternate forms of the LNS showing even higher reliability coefficients ($r=.75$) (Kaufman & Lichtenberger, 2002; Hood, Pulvers & Spady, 2013).

This test consists of 27 trials with sequences that range from two stimuli (e.g., B-4) up to a maximum of eight stimuli (e.g., 8-E-7-F-5-A-3-Z). For this test, the researcher verbally presents different sets of increasingly longer sequences of intermixed letters and numbers at a rate of one per second. After each sequence, participants repeat the numbers in numerical order followed by the letters in alphabetical order. Sequences were presented with three trials at each length, and discontinued when participants failed on three consecutive trials. In order to minimize practice effects, three alternate forms of the test were created that varied in combinations of letters and numbers. In order to reduce the variability of test administration, the researcher played a pre-recorded audio file of the LNS test in place of administering the test live to ensure the test delivery was consistent across all participants.

Procedure

Before the experiment. All participants were recruited through the Human Participant Pool (HPP) at California State University San Marcos. Participants were required to sign up for both sessions during this time. The HPP description explained that this was a two-part exercise study and informed participants that they would be required to visit the lab for two separate
sessions, approximately one week apart. The description also listed certain requirements for each session, such as appropriate exercise apparel (no open-toed shoes, mini-skirt, jeans, etc.), to abstain from eating one hour prior to each session, and not to engage in strenuous lower-body physical activity for 12 hours prior to each session. Additionally, this description also listed certain inclusion/exclusion criteria such as being between the ages of 18-26 and the exclusion of women who are or think they may be pregnant.

*Day 1- VO2 maximal test.* Once the participant arrived, the researcher ensured that individuals were dressed in appropriate exercise apparel. Then the researcher obtained informed consent and ensured participants understood the requirements and procedures of the study. The researcher also confirmed that all participants were available to come back the following week at the same time. Upon obtaining informed consent, participants completed a medical and health questionnaire to ensure they were healthy enough for exercise. Participants then completed their first working memory task (LNST). Participants heard a string of intermixed letters and numbers and were asked to repeat the sequence back to the researcher, with the numbers first in numerical order and the letters in alphabetical order. Then participants completed an online questionnaire, including the International Physical Activity Questionnaire (IPAQ-LF) in order to assess levels of physical activity, as well as several demographic questions. Following completion of the questionnaire, height and weight was assessed and participants were asked to attach the chest-based heart rate monitor. Following this task, participants performed the graded VO2 maximal exercise test to determine their maximal aerobic capacity. Once participants reached volitional fatigue the test was stopped and they were instructed to continue pedaling for three to four minutes in order to allow their body to cool down. Researchers monitored participants for five
minutes following this exercise test and provided them with water. At the end of the session, researchers confirmed their follow-up appointment and thanked them for their participation.

_Day 8- Exercise intervention._ Upon arrival to the lab, participants were reminded of the procedures and the researchers verified there had been no changes to their medical status. Then participants engaged in a single 30-minute bout of aerobic exercise (including warm-up and cool-down) on a cycle ergometer of low, moderate or high intensity or a no-exercise resting control. The four-exercise intensity conditions were based on the participants' maximal watts (Wmax) attained in the VO2 max test, which represented a percentage of the individual’s max capacity. Those in the control condition sat on the ergometer for 30 minutes without pedaling. All of the exercise conditions included a 3-minute warm-up and 2-minute cool-down. Those in the low and moderate condition exercised at a consistent intensity for entire session. Those in the high condition engaged in interval exercise that fluctuated between low and high intensity exercise. Additionally, during exercise participants were asked every 5 minutes to report their feelings of perceived exertion (RPE).

Immediately following the two-minute cool-down, participants completed the second LNS test. Fifteen minutes following the cessation of exercise, participants completed the third LNS test. Then participants were debriefed about the study and given a referral sheet to the student health and counseling services office. Feedback was also provided to all participants regarding their performance on the VO2 maximal test in terms of their aerobic fitness. Participants were then thanked for their time.

**Results**

First, descriptive statistics were conducted on working memory scores to assess normality, skewness and check for any potential outliers. Histograms suggested that the data
were normal and that there were no outliers (See Appendix A). Descriptive statistics were also conducted on total active minutes and total sitting minutes within the last week. Visual inspection of the histograms for these variables revealed the data were positively skewed. In an effort to reduce the skewness, a square root transformation was chosen, as this type of transformation is commonly used for positively skewed data (Howell, 2010). Descriptives were re-run on the transformed data and histograms suggested that the square root transformation was successful in reducing the positive skewness, resulting in data that were more normally distributed.

Preexisting differences among groups were also tested in order to ensure there were no initial confounds for this study. One-way ANOVA’s were conducted on baseline working memory scores and fitness level between the different exercise conditions. Results showed that there were no significant differences in baseline working memory scores between the control condition ($M=15.97$, $SD=1.52$, $N=30$), low intensity ($M=15.37$, $SD=2.49$, $N=30$), moderate intensity ($M=15.60$, $SD=2.22$, $N=30$) and high intensity ($M=16.33$, $SD=2.25$, $N=30$) conditions ($F(3,116) = 1.17$, $p = .33$). Results also showed that there were no significant differences in average fitness level between the control condition ($M=33.45$, $SD=5.67$, $N=30$), low intensity ($M=34.76$, $SD=7.65$, $N=30$), moderate intensity ($M=37.41$, $SD=7.94$, $N=30$) and high intensity ($M=36.88$, $SD=8.81$, $N=30$) conditions ($F(3,116) = 1.78$, $p = .16$). Together, these results suggest that random assignment to condition was successful.

The final preliminary analysis was a one-way ANOVA conducted as a manipulation check to determine whether average heart rate during exercise differed (See figure 1). The results revealed a significant main effect for condition ($F(3, 116) = 528.25$, $p < .001$, $\eta^2 = .93$). Specifically, average heart rate for all conditions differed significantly from one another, with
the lowest average heart rate seen in the control condition ($M=76.56$, $SD=7.51$, $N=30$), followed by the low intensity condition ($M=127.84$, $SD=9.23$, $N=30$), moderate intensity condition ($M=148.61$, $SD=13.79$, $N=30$), and high intensity condition with the highest average heart rate ($M=171.55$, $SD=6.42$, $N=30$). These results suggest that the exercise conditions were successful in inducing the different exercise intensities.

Analysis of hypotheses

Assumptions for all relevant statistical tests including the mixed model and one-way ANOVA’s as well as bivariate correlations were tested prior to any analysis. Assumptions for the mixed-model and one-way ANOVA include normal distribution of data, equal variances, and independence of observations. In addition, for the mixed model ANOVA, there is also the assumption of sphericity. Based on visual inspection of the histograms, all working memory test data were normally distributed. For the Levene’s test of equality of error variances, two out of the three working memory tests met this assumption ($p > .05$). Given that the ANOVA is robust to this type of violation and that only one of the working memory tests was in violation, the researcher chose to proceed with the planned analysis. Thus, results for this analysis should be
interpreted with caution. Finally, both the independence of observations and sphericity assumptions were also met. Assumptions for correlations include normality, homoscedasticity, linearity for each variable and independence of observations. Overall, the assumptions for bivariate correlations were met with the exception of normality. The time spent active and time spent sitting data were positively skewed so a square root transformation was performed to help reduce the skewness. Scatterplots indicated that both variables met the assumptions of linearity and homoscedasticity. Finally, independence of observations was also met as the researcher made every effort to ensure that no single data point influenced another.

The initial analysis conducted was a 3 (baseline, Post 1 and Post 2) X 4 (exercise condition) mixed model ANOVA, with exercise intensity as the between-subjects factor (low, moderate, high, and control) and time when cognition is tested as the within-subjects factor (baseline, two minutes after and 15 minutes after). The results yielded a main effect of time, $F(2, 232) = 9.05, p<.001, \eta^2 = .07$, however the interaction between time and condition was not significant, $F(6, 232) = .48, p=.82, \eta^2 = .01$. Follow-up comparisons revealed that working memory scores were significantly higher immediately following exercise ($t(232) = -3.15, p=.002, d = -.41, M_{marginal} = 16.38, SE = .22$) and 15 minutes following exercise ($t(232) = -3.90, p<.001, d = -.52, M_{marginal} = 16.54, SE = .25$) compared to baseline working memory scores ($M_{marginal} = 15.82, SE = .20$). Thus regardless of condition, participants’ working memory increased immediately after and 15 minutes following the intervention (See figure 2).
Hypothesis 1a-1d

A series of repeated measures ANOVAs were conducted to test the first set of hypotheses regarding the effect of each exercise condition on changes in working memory (within-subject comparisons). The first hypothesis was that working memory performance for the resting control condition would remain stable over time. Results indicated that there were no significant differences between baseline working memory ($M=15.97$, $SD=1.52$, $N=30$), immediately post ($M=16.27$, $SD=1.89$, $N=30$), and fifteen minutes post working scores ($M=16.47$, $SD=2.42$, $N=30$) for the control condition, $F(2, 58) = 1.35, p=.27$ (See figure 3). Follow up analysis indicated no difference in working memory scores immediately following ($M=16.27$, $SD=1.89$, $N=30$), $t(58) = -1.01, p=.33$, or fifteen minutes following the rest condition ($M=16.47$, $SD=2.42$, $N=30$), $t(58) = -1.61, p=.12$, when compared to baseline ($M=15.97$, $SD=1.52$, $N=30$). The second hypothesis was that working memory performance would increase compared to baseline immediately following low intensity exercise, but return to baseline levels 15 minutes following exercise. Results revealed that there was a main effect for time when working memory was tested for the low intensity condition, $F(2, 58) = 5.15, p=.009, \eta^2 = .15$ (See figure 4).
Additional follow-ups revealed that working memory scores were higher 15 minutes following exercise ($M= 16.43, SD= 2.19, N=30), t (58) = -3.15, p=.004, d= -.83$, but there was no significant difference immediately following exercise ($M= 15.93, SD= 2.36, N=30), t (58) = -1.57, p=.13$, compared to baseline ($M= 15.37, SD= 2.48, N=30$).

Figure 3: Changes in working memory for the control condition

Note: Error bars represent 95% CI around the mean using the within-subjects error term.
The third hypothesis was that working memory performance would increase immediately following and 15 minutes following moderate intensity exercise compared to baseline. The results indicated no significant main effect of time for the moderate intensity condition, $F (2, 58) = 2.72, p=.07$ (See figure 5). However, follow-up planned comparisons showed that working memory scores were higher fifteen minutes following exercise ($M=16.33, SD= 2.37, N=30$), $t (58) =-2.23, p=.03, d=-.57$, but no difference was found immediately following exercise ($M=16.20, SD= 2.34, N=30$), $t (58) =-1.62, p=.12$, compared to baseline ($M=15.60, SD= 2.22, N=30$). The fourth hypothesis was that working memory performance would decrease compared to baseline immediately following high intensity exercise but increase compared to baseline 15 minutes following high intensity exercise. Results showed no main effect of time for the high intensity condition, $F (2, 58) = 1.76, p=.18$ (See figure 6). Planned comparisons also indicated no significant difference in working memory scores immediately following ($M=17.13, SD= 3.07, N=30$), $t (58) =-2.01, p=.06$, or fifteen minutes following high intensity exercise ($M=16.93, SD= 3.65, N=30$), $t (58) =-1.24, p=.22$, when compared to baseline ($M=16.33, SD= 2.25, N=30$).
**Hypotheses 2a-2c**

To analyze hypotheses 2a-2c, a set of one-way ANOVA’s were conducted to examine how the exercise intensity conditions influenced post working memory performance only (between-subject comparisons). Hypotheses 2a/2b stated that working memory scores immediately following exercise would be lower for high intensity but higher for moderate intensity exercise, when compared to the other conditions. There was no significant main effect
of exercise intensity on working memory immediately following the exercise, $F (2, 87) = 1.74$, $p=.18$. Hypotheses 2c stated that working memory 15 minutes following exercise would be significantly higher for moderate and high-intensity compared to low-intensity exercise. The results also revealed no main effect of exercise condition fifteen minutes following the exercise, $F (2, 87) = .39$, $p=.68$. Thus, working memory scores immediately post and fifteen minutes post low, moderate and high intensity exercise did not differ.

**Hypotheses 3a & 3b**

Finally, to examine the relationship between total amounts of time spent active (engaging in physical activity) and sitting within the last week and baseline working memory scores, two separate Pearson product moment correlations were conducted. It was hypothesized that individuals who reported more time engaging in physical activity for the last seven days would have higher baseline working memory scores compared to those who report less time. However, the results showed that the relationship between time spent active and baseline working memory scores was not significant, $r (117) = .15$, $p=.09$. The last hypothesis was in regards to the amount of time-spent sitting and baseline working memory scores, such that those who reported more time spent sitting in the last seven days would have lower baseline working memory scores compared to individuals who reported lesser amounts of time. The correlation coefficient between time spent sitting and baseline working memory was not significant, $r (117) = -.06$, $p=.51$. Overall, these results suggest no relationship between reported time spent active or sitting and baseline working memory.

**Discussion**

The purpose of the study was to determine how different intensities of aerobic exercise influence working memory performance immediately after and fifteen minutes after exercise
cessation. In addition, we were also interested in gaining a better understanding of the relationship between the amount of physical activity one engages in and their baseline working memory. Overall, our results showed that working memory scores increased over time regardless of the exercise condition. All participants, regardless of whether they exercised got better at the working memory task over time. Further analysis of the hypotheses are described below.

**Changes in working memory scores for the exercise conditions**

Hypothesis 1a was supported. Results revealed no significant differences between the three measures of working memory for the control condition. This finding helps support the notion that exercise does in fact enhance working memory following exercise because those who did not engage in any exercise showed no change in their working memory performance. However, hypotheses 1b was not supported and the results were actually in the opposite direction than predicted. Those who engaged in a low intensity bout of aerobic exercise had no change in their working memory scores immediately following but scores were significantly higher 15 minutes after exercise. Very little research has been done examining the effects of low intensity exercise on working memory performance and this is one of the first studies to examine this relationship. These results suggest that the benefits of low intensity exercise may be most prominent following a short delay rather than immediately following exercise. However, further research is needed to replicate this finding with a larger sample size. Hypothesis 1c was also only partially supported. It was predicted that moderate intensity exercise would result in higher working memory scores following exercise for both time points. Those who engaged in moderate exercise saw no change immediately following exercise but scores were higher 15 minutes following. Despite the common finding that moderate intensity exercise is beneficial for many different aspects of higher order cognition immediately following exercise, the current study
results do not support this finding. It may be that our moderate intensity condition over time was above what our participants would characterize as moderate intensity exercise. Given that participants had to exercise for 25 minutes at 50% of their max, over the course of the exercise participants may have started to feel fatigued and tired if they were not used to exercising at that intensity. Finally, hypothesis 1d was not supported and the trend was actually in the opposite direction, although there was a marginally significant difference for the high intensity group from baseline working memory scores to immediately following exercise ($p=.06$). This finding also runs counter to the transient hypofrontality theory (THT), which suggests that higher intensity exercise monopolizes available brain resources resulting in diminished cognitive performance on tasks that rely on the prefrontal cortex (Dietrich, 2003). However, it may be that because we choose to utilize high intensity intervals (HIIT) rather than consistent high intensity exercise, participants might have been able to recover during the exercise and may not have truly felt like they were engaging in high intensity exercise. Even though average heart rate for participants in this condition was significantly higher compared to the other groups, providing a recovery period may have made the exercise more manageable and not as exhaustive as consistent high intensity exercise. Thus, future research could examine how shorter bouts of consistent exercise influence working memory.

**Exercise intensity on post working memory scores**

We also wanted to compare working memory scores following exercise between the exercise conditions to see if a particular intensity resulted in higher working memory scores. Hypotheses 2a and 2b that working memory immediately following exercise would be lower for high intensity but higher for moderate intensity exercise were not supported. We found no significant differences between immediately post working memory scores for the low, moderate
and high exercise conditions. These results are also not in line with previous research that suggests that moderate intensity exercise is beneficial and high intensity exercise is detrimental to complex measures of cognition (Dietrich & Sparling, 2004; Martins et al., 2013). Given our relatively small sample size per condition it may be that we did not have an adequate number of participants in order to detect an effect. It also could be that the participants in this study may not have perceived our exercise intensity conditions as they were defined by the study. Histograms of the maximal VO₂ data showed that the distribution was positively skewed, indicating that more of our sample was of lower fitness. Additional analysis also revealed a significant gender difference in fitness level among our sample \( t(38.73) = 5.29, p < .001 \) with males \( (M=42.30, SD= 8.87, N=31) \), being significantly more fit compared to females \( (M=33.30, SD= 5.63, N=89) \). Given that, the majority of our sample was on the lower end of the fitness distribution it could be that some of the participants perceived their bout of exercise as more intense (See Appendix B). Particularly for women because they tended to be less fit than their male counterparts. Future research could conduct a similar study with equal numbers of males and females to see if results remain the same. Hypothesis 2b was also not supported. It was predicted that working memory performance 15 minutes following exercise would be higher for both the moderate and high-intensity exercise conditions compared to low-intensity condition. However, our results showed no difference in working memory scores 15 minutes following exercise for the different conditions. Very little research has been conducted on the delayed effects of different exercise intensities on working memory performance. Given the relatively small sample sizes in each intensity group, further research is needed in order to gain a better understanding of how different intensities of exercise influence post working memory performance.
Relationship between the amount of reported physical activity and sitting minutes and baseline working memory

Additionally, we wanted to understand the relationship between reported amounts of physical activity and time spent sitting, and how those variables relate to baseline working memory performance. It was predicted that individuals who self-report more time spent engaging in physical activity (among multiple domains) for the previous seven days, would also have higher baseline working memory scores and those who spent more time sitting for the previous seven days, would have lower working memory scores. However, our results did not support predicted hypotheses, although there was a small, positive trend for total time spent engaging in physical activity and higher baseline working memory scores ($r (117) = .15, p=.09$). Understanding the relationship between these variables was not the main focus of this research project and more participants may have been needed in order to detect a significant relationship. However, it is still interesting that in our relatively small sample size we were able to detect a marginally significant relationship.

Strengths and Limitations

This study was one of the first to compare different exercise intensities on subsequent working memory performance at two different time points. Little research has been devoted to understanding how low intensity exercise influences cognition, which is largely due to the difficulty associated with defining low intensity exercise. However, our study was able effectively induce different exercise conditions as evidenced by significant differences in average heart rate for each condition. In addition, many of the working memory measures that have been used in this area take long to administer and complete and may not be capturing the truly immediate effect of exercise on cognition. The working memory task chosen for this study
takes anywhere from 2-5 minutes to administer and thus is able to provide a quick snapshot of working memory. Finally, this study was one of the first to examine the delayed effects of different exercise intensities on working memory specifically. Most of the previous research has not examined how long the effects last and our study was one of the first to show the delayed benefits of low and moderate exercise for working memory.

This study also had some notable limitations. First, most of our sample was made up of female (74%) who identified as White (32%) or Hispanic (41%). Based on the demographics of our sample it is not clear how well these results generalize to males and non-southern California university students. However, it is worth noting that most of the literature on the effects of exercise on cognition tends to focus on highly fit males. Our sample demographics may also be considered a strength as we were able to recruit mostly women and so this research could provide additional insight on how exercise influences cognition. The working memory test we used could also be seen as a limitation in this study. While this working memory test is a subtest of the widely used Wechsler Intelligence Test (Wechsler, 1997), and purports to measure working memory abilities such as visuospatial manipulation, attention and processing speed, it may not be a pure measure of working memory. Also, a major finding was that regardless of condition working memory scores increased over time, regardless of condition (See Appendix C). This could be due to practice effects as a result of repeated administration and participants learning the test rather than a true measure of working memory. Future research interested in understanding the relationship between exercise and post working memory performance should attempt to construct a more reliable measure that is quick to administer. Another limitation of our study was the relatively sample size in each of our conditions. Even though we had 120 participants total in our study, there was only 30 participants per condition. Future research
might consider only comparing one or two exercise intensities conditions using the same amount of participants within a study in order to gain a better understanding. A final limitation of this study was the use of a cycle as the mode of exercise. A common complaint among most if not all participants was how uncomfortable the bike seat was. This may have also had to do with the low level of familiarity with cycling as most of the sample reported little to no engagement in cycling exercise the past week. While this form of exercise was chosen in order to lower the risk of injury while exercising (as opposed to a treadmill) it was clear that many participants perceived the exercise as less enjoyable because of the uncomfortableness associated with the bike seat. Future researchers might consider assessing the type of exercise their participants typically engage in and then using that information to assign a bout of exercise that is line with the habits of their sample.

Conclusions

The results of this study add to the current body of research examining the effect of acute exercise intensity on post working memory performance. Specifically, our results suggest that regardless of the exercise condition, working memory scores increased from baseline to immediately post and 15 minutes following exercise. We also found that performance was significantly higher 15 minutes following low and moderate exercise when compared to baseline performance. Although the results were not significant, a marginally significant difference was found between baseline working memory and immediately post working memory scores for the high intensity group. Overall, these results suggest that low and moderate intensity exercise may have the greatest impact on working memory following a delay, whereas the effect of higher intensity exercise may be most apparent immediately following the exercise.
References


Prefrontal regions play a predominant role in imposing and attentional 'set': Evidence from fMRI. Cognitive Brain Research, 10(1-2), 1-9. doi:10.1016/S0926-6410(00)00015-X


Appendix A

Histograms of the working memory scores at three different time-points
Appendix A

![Histogram with statistical data]

- **Mean:** 16.64
- **Std. Dev.:** 2.934
- **N:** 120

Frequency vs. Post working memory2 (15 mins)
Appendix B

Histogram of VO₂ data

Mean = 35.17
Std. Dev. = 6.975
N = 118
Appendix C

Correlations between the three different working memory measures

<table>
<thead>
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<th>Correlations</th>
<th>Baseline working memory</th>
<th>Post working memory1 (immediately after)</th>
<th>Post working memory2 (15 mins)</th>
</tr>
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<td>Baseline working memory</td>
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<td>.673**</td>
</tr>
<tr>
<td>Sig. (2-tailed)</td>
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<td>.000</td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>120</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>Post working memory1 (immediately after)</td>
<td>Pearson Correlation .650**</td>
<td>1</td>
<td>.739**</td>
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<tr>
<td>Sig. (2-tailed)</td>
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<td>.000</td>
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<tr>
<td>N</td>
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<td>120</td>
<td></td>
</tr>
<tr>
<td>Post working memory2 (15 mins)</td>
<td>Pearson Correlation .673**</td>
<td>.739**</td>
<td>1</td>
</tr>
<tr>
<td>Sig. (2-tailed)</td>
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</tr>
<tr>
<td>N</td>
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</tbody>
</table>

** Correlation is significant at the 0.01 level (2-tailed).