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Working Memory Performance across Development and Following Acute Exercise

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WORKING MEMORY PERFORMANCE ACROSS DEVELOPMENT AND FOLLOWING ACUTE EXERCISE

A Thesis Presented

by

PATRICE L. STERING

Submitted to the Graduate School of the
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ABSTRACT

WORKING MEMORY PERFORMANCE ACROSS DEVELOPMENT AND FOLLOWING ACUTE EXERCISE

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This thesis investigates the developmental trajectory of visuo-spatial working memory as well as the potential influence of acute exercise on working memory performance. Individuals between the ages of 6 and 25 years were randomly assigned to a 30-minute bout of exercise on an elliptical trainer or to a no-exercise control condition. Participants then performed a computerized N-back task to assess working memory. Developmental results suggest that working memory ability continues to develop into early adulthood with the exact trajectory depending on the cognitive demand of the task being assessed. No difference in working memory performance was found between the exercise and control conditions. Thus, acute exercise did not influence performance on the present working memory task, suggesting a need for more research in this area.

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CHAPTER I

INTRODUCTION

Working memory is considered an executive function that is involved in many day-to-day tasks, such as holding information in mind, reasoning, and decision-making (e.g., G. A. Miller, Galanter, & Pribram, 1960). For example, when grocery shopping, we may need to estimate how much we have left to spend as we continue to shop. Working memory allows us to hold in mind the cost of groceries already in our cart while simultaneously looking for the next item on our list and adding to the current total the cost of additional items we select. This ability has been studied extensively in adults (for reviews see Baddeley, 2003; Conway et al., 2005), but research assessing working memory from a developmental perspective remains limited. Two studies looking at working memory performance from childhood through adolescence reveal inconsistent results, with one study finding linear growth in the developmental trajectory (Gathercole, Pickering, Ambridge, & Wearing, 2004) and the other finding curvilinear growth (Luciana, Conklin, Hooper, & Yarger, 2005). One goal of the present study was to address this inconsistency by examining working memory performance across participants ages 6 through 25 years.

Various forms of working memory training have led to improvements in working memory capacity and performance (for review see Morrison & Chein, 2011). Other non-working memory specific techniques have also been found to significantly improve working memory performance, including mindfulness training in college-aged adults (Zeidan, Gordon, Merchant, & Goolkasian, 2010), positive reinforcement in children with autism (Baltruschat et al., 2011), and acute exercise in adults (Pontifex, Hillman, Fernhall, Thompson, & Valentini, 2009; Sibley & Beilock, 2007). These studies suggest that various forms of training have the potential to positively influence working memory in specific populations. In line with this suggestion, a second goal of the present study was to assess the influence of an acute exercise manipulation on working memory performance.

Research focusing on the link between physical activity and cognitive abilities suggests that physical activity may preferentially influence executive function abilities (e.g., Guiney & Machado, 2013; Kramer, Colcombe, McAuley, Scalf, & Erickson, 2005; Kramer et al., 1999; Tomporowski, 2003). Previous studies have found positive relationships between working memory capacity and physical activity levels (Deeny et al., 2008; Pluncevic-Gligoroska, Manchevska, Sivevska-Smilevska, & Bozhinovska, 2010). However, the conclusions that can be drawn from these results are limited because the studies are correlational. A more effective approach to determine whether physical activity improves working memory is to conduct a study with an experimental design. Through use of an experimental approach, acute exercise has been shown to positively impact working memory performance in adults (Pontifex, et al., 2009; Sibley & Beilock, 2007). No studies, to my knowledge, have experimentally examined the influence of acute exercise on working memory performance across development. Physical activity may affect children or adolescents differently than adults. Accordingly, a third aim of the current study was to examine potential developmental differences in the influence of acute exercise on working memory in participants between the ages of 6 and 25.

The following literature review discusses research concerning working memory, working memory across development, physical activity and cognition, and physical activity and working memory. The gaps in the current literature are addressed and the present study is introduced.

Literature Review

Working Memory

Working memory is a cognitive process that falls under the umbrella of executive functions and involves the active storage, maintenance, and manipulation of information to be retrieved within a short time period (e.g., Kane & Engle, 2002). Working memory also supports complex cognitive functions, such as reasoning and decision-making (G. A. Miller, et al., 1960). Baddeley and Hitch (1974) developed a model to describe the underlying processes involved in working memory. This model, which has undergone expansion and refinement (Baddeley, 2000), consists of a central executive component and three slave components: the phonological loop, the visuo-spatial sketchpad, and the episodic buffer. The central executive acts as a supervisory system by controlling and coordinating information flow between the other components. The phonological loop processes verbal information, while the visuo-spatial sketchpad processes visual and spatial information (e.g., Baddeley & Hitch, 1974). The episodic buffer component is responsible for linking and integrating information between the phonological loop, visuo-spatial sketchpad, and long-term memory systems (Baddeley, 2000).

Working memory has been assessed in numerous research studies using a variety of tasks and paradigms (for reviews see Baddeley, 2003; Conway, et al., 2005). One such paradigm, the N-back, was originally developed by Welford (1952) and first used to measure short-term memory experimentally by Kirchner (1958). In an N-back task, participants are instructed to indicate the repetition of a stimulus that occurs before the current trial (e.g. one, two, or three trials back). Performance on the N-back is used to measure a participant's ability to acquire, retain, and update rapidly changing information (Kirchner, 1958). The current study used an N-back task, containing visuo-spatial information, to assess working memory abilities across development.

Working Memory across Development

Using the subcomponents of the original Baddeley and Hitch working memory model (1974), Gathercole and colleagues (2004) examined the structural organization of working memory across development in over 700 children ages 4 to 15 years. Three verbal storage tasks were used to measure the phonological loop, three visuo-spatial short term memory tasks assessed the visuo-spatial sketchpad, and three complex memory span tasks tapped into the central executive component of working memory. Using standardized performance on these nine measures, broadly similar linear improvements were observed from age 4 to 14 years with performance leveling off between ages 14 and 15 years. One task, however, illustrated a different developmental pattern. The Visual Patterns Test, a measure of visual short-term memory, reached an asymptote in performance level at 11 years. With the exception of this one measure, results suggest linear improvement across all subcomponents of the Baddeley and Hitch working memory model from age 4 to 14 years.

It is worth noting that Gathercole and colleagues (2004) did not test individuals beyond age 15, and working memory may not be fully developed by this time point. Given this limited age range, it is not possible to determine the age at which working memory reaches the asymptote of performance. The present study sampled a broader age range to evaluate working memory from childhood into young adulthood.

In a related study, Luciana and colleagues (2005) assessed spatial working memory from age 9 to 20 years. This study adds to the literature by assessing working memory capacity through adolescence. Several working memory tasks differing in their demand for cognitive control were used. As hypothesized, the authors found that the ability to perform tasks requiring less cognitive control showed earlier development, whereas the ability to accomplish tasks requiring higher levels of control developed later. Performance of recall-guided action, a relatively simple working memory task, did not show developmental changes after 11 to 12 years of age. Completion of tasks requiring maintenance and manipulation of spatial information showed developmental change up to 13 to 15 years, whereas execution of the task requiring strategic organization, and thus the highest level of demand, revealed development change up to 16 to 17 years.

As opposed to the linear developmental trajectory observed by Gathercole and colleagues (2004), results of the study by Luciana and colleagues (2005) suggest that working memory develops in a curvilinear fashion and the specific developmental path is dependent upon the cognitive demands being assessed. Given the inconsistencies in these two studies, the present study sought to determine whether the developmental trajectory of performance on the present study’s visuo-spatial working memory task is linear or curvilinear in nature.

Physical Activity and Cognition

Research examining the benefits of physical activity is not a new endeavor (e.g., Haskell, Montoye, & Orenstein, 1985; Kannel & Sorlie, 1979; Warburton, Nicol, & Bredin, 2006). Recent work exploring the relationship between exercise and cognitive abilities suggests that physical activity differentially impacts specific aspects of cognition rather than exerting global benefits (for review see Tomporowski, Davis, Miller, & Naglieri, 2008). Specifically, physical activity has been shown to produce stronger effects on executive functions (e.g., Colcombe & Kramer, 2003; Guiney & Machado, 2013; Hillman, Snook, & Jerome, 2003; Pontifex, et al., 2009). The effect of physical activity on executive processes has been characterized in the research literature as the 'executive function hypothesis' (e.g., Tomporowski, et al., 2008). Executive functions include, but are not limited to, cognitive flexibility, working memory, inhibitory control, planning, and problem solving (e.g., Chan, Shum, Toulopoulou, & Chen, 2008; E. K. Miller & Cohen, 2001; Norman & Shallice, 1986). Research examining the link between exercise and cognition continues to explore these relatively selective effects.

From a neurological perspective, the impact of exercise on executive functions may be the result of changes in or strengthening of synaptic connections in the brain. Chronic physical activity has been found to increase the expression of several growth factors in the rat brain, including brain-derived neurotrophic factor (BDNF; Neeper, Gomez-Pinilla, Choi, & Cotman, 1995; Oliff, Berchtold, Isackson, & Cotman, 1998). BDNF mediates learning through action on synaptic plasticity (Gomez-Pinilla, Ying, Roy, Molteni, & Edgerton, 2002; Vaynman, Ying, & Gomez-Pinilla, 2003), and thus the influence of physical activity on specific areas of cognition may be a function of plasticity via BDNF or similar growth factors.

Much of the work assessing the link between physical activity and cognition examines the influence of chronic physical activity (e.g., Colcombe & Kramer, 2003; Kramer, et al., 1999) or the relationship between physical fitness and cognitive abilities (e.g., Hillman, Belopolsky, Snook, Kramer, & McAuley, 2004; Hillman, Weiss, Hagberg, & Hatfield, 2002; Pontifex et al., 2011). However, benefits have also been observed following acute bouts of exercise (for review see Tomporowski, 2003). Some researchers have considered this boost in cognitive performance following acute exercise a result of increased blood flow in the brain, leading to increased levels of arousal (e.g., Brisswalter & Legros, 1995; Reilly & Smith, 1986). For example, Chmura and colleagues (1994) found a direct relationship between discriminative choice-response response time (RT) and plasma catecholamine levels (Chmura, et al., 1994). However, the benefit of physical activity on some abilities and not others imply something other than a global boost in arousal. The differential benefits suggest that specific areas or circuits in the brain, and thus specific cognitive abilities, may be more sensitive to exercise-induced arousal than other systems.

Acute exercise has been shown to enhance cognition, specifically when tasks require a greater degree of cognitive control relative to tasks requiring less control (Hogervorst, Riedel, Jeukendrup, & Jolles, 1996; Lichtman & Poser, 1983; Tomporowski, 2003). The present study used a task requiring both attention and cognitive control to assess the effect of acute exercise on working memory performance in children, adolescents, and young adults.

Physical Activity and Working Memory

Researchers investigating the relationship between exercise and cognitive abilities have correlated measures of fitness with working memory performance (Deeny, et al., 2008; Pluncevic-Gligoroska, et al., 2010). Pluncevic-Gligoroska and colleagues (2010) obtained self-report data on the weekly exercise habits of 90 young adults. The questionnaire data were used to divide participants into three groups according to level of physical activity: sedentary individuals, individuals involved in recreational activities, and athletes. Participants were given the Wechsler Digit Span Test (Wechsler, 1997), a measure of working memory abilities. Analyses revealed significant differences in mean working memory score between the three groups such that higher mean scores were associated with higher levels of physical activity. This finding provides support for the hypothesis that physical activity positively impacts working memory capacity.

Exercise level has also been found to modify the relationship between cognitive function and risk for Alzheimer’s disease in middle-aged adults (Deeny, et al., 2008). Deeny and colleagues used a modified Sternberg working memory task (Sternberg, 1966) to assess cognitive function and a self-report questionnaire to quantify participant’s exercise level. At-risk status for Alzheimer’s disease was determined by APOE genotype; those with the e4 allele are considered at increased risk for the disease (e.g., Corder et al., 1993; Saunders et al., 1993). Results revealed an association between high physical activity level and faster RT on several conditions of the working memory task in carriers of the e4 allele, but not in non-carriers. Although these results are correlational, the study suggests a relationship between exercise and working memory performance.

Currently, much of the research linking physical activity and working memory is limited to adult populations. However, one recent study investigated the relationship between physical fitness and spatial working memory capacity in preschool children (Niederer et al., 2011). Children participated in a 20-minute shuttle run to test their aerobic endurance. Spatial working memory abilities were assessed with a validated subtest for preschoolers (Intelligence and Development Scales; Grob, Meyer, & Hagmann-von Arx, 2009). Nine months later, the tests were repeated, allowing for both cross-sectional and longitudinal analyses of the data. Surprisingly, analyses revealed no significant correlations between working memory performance and aerobic endurance. Although these results suggest that aerobic fitness might not be associated with working memory capacity in pre-school aged children, it may be possible that an experimental manipulation, such as an acute bout of exercise, would lead to a difference in working memory performance. The current study assessed this possibility in older children as well as adolescents and adults.

Each of the previously discussed studies assessing the relationship between working memory and physical activity (Deeny, et al., 2008; Niederer, et al., 2011; Pluncevic-Gligoroska, et al., 2010) were correlational and therefore a causal direction could not be determined. A more effective approach in evaluating this relationship is through an experimental design where participants are randomly assigned to a physical activity condition or to a no-exercise control condition. The following two studies employed experimental designs in examining the link between acute physical activity and working memory.

To measure working memory capacity at varying levels of cognitive demand, Pontifex and colleagues (2009) used a modified Sternberg working memory paradigm (Sternberg, 1966) with task set sizes of three, five, and seven letters. Testing was administered nine times for each participant: before the start of, immediately after, and 30 minutes after a bout of aerobic exercise, resistance exercise, and a seated rest condition. Results indicated significantly faster mean RT immediately after and 30 minutes after aerobic exercise relative to the control condition. When compared to resistance exercise or seated rest, aerobic exercise also led to a greater reduction in RT from baseline for task set sizes five and seven. These findings suggest that acute exercise leads to improved performance on tasks involving increased working memory demands.

A similar study assessed participants' working memory abilities in two counterbalanced conditions: at baseline and immediately after a 30-minute bout of aerobic exercise on a treadmill (Sibley & Beilock, 2007). Prior to analyses, participants were split into quartiles according to baseline working memory performance. Results indicated that only those in the lowest quartile significantly increased their working memory score between the baseline and exercise conditions, suggesting that the influence of exercise on working memory is not uniform across all individuals. Given these results, Sibley and Beilock (2007) suggest that researchers exploring the effects of physical activity on cognition may find different outcomes depending upon the existing cognitive abilities of those being tested. With the developmental sample in the present study, it was predicted that younger children who have less developed working memory abilities would show a greater benefit from acute exercise than older participants whose working memory abilities are more fully developed.

Previous studies assessing the influence of acute exercise on working memory have been limited to adult populations (Pontifex, et al., 2009; Sibley & Beilock, 2007) and assessing this influence in a developmental sample is important because acute exercise has the potential to exert differential influences at various points in development. The present study addressed this possibility through use of an experimental design examining the influence of acute exercise on working memory performance in 6 to 25 year olds.

Overview of Study

The present study examined working memory performance across development by sampling individuals between the ages of 6 and 25 years. Previous research suggests that working memory performance improves during childhood and early adolescence (Gathercole, et al., 2004; Luciana, et al., 2005). However, there is inconsistency in the developmental trajectories detected. The current study was designed to address this discrepancy by assessing visuo-spatial working memory performance in a broader age range, up to 25 years as opposed to 15 and 20 in the previous studies (Gathercole, et al., 2004; Luciana, et al., 2005), respectively. Performance on the present visuo-spatial working memory task was predicted to improve in childhood and reach peak performance in late adolescence or early adulthood.

A second aim of the current study was to explore the potential benefits of acute exercise on working memory performance. Researchers have found that physical activity training programs have a positive influence on working memory performance (Hansen, Johnsen, Sollers, Stenvik, & Thayer, 2004; Stroth et al., 2010). Given the positive impact of longer-term exercise, a question remains about whether acute exercise can elicit a similar effect. Using an experimental design, the present study randomly assigned participants to an acute exercise condition or to a no-exercise control condition. It was predicted that participants who engaged in acute exercise prior to the task would demonstrate better performance than those who did not engage in physical activity, as seen in previous studies (Pontifex, et al., 2009; Sibley & Beilock, 2007).

A third goal of the current study was to assess the influence of acute exercise on working memory performance across development. Given the lack of research addressing this influence from a developmental perspective, the possible differential impact of acute exercise on working memory with age is unknown. The results found by Sibley and Beilock (2007), however, suggest that those lowest in working memory capacity may show a disproportionate change in performance following acute exercise. Thus, the present study predicted a greater influence of acute exercise in younger participants, who have less developed working memory abilities, than older participants with greater working memory abilities.

CHAPTER II

METHOD

Study Design

The current experiment was part of a larger project assessing the influence of acute exercise on various cognitive abilities across development, including attention, working memory, cognitive control, and response inhibition. Using the data obtained from a computer-based visuo-spatial working memory task, the present study assessed the influence of acute exercise on working memory performance across development. Participants were randomly assigned to an exercise condition (30 minutes of aerobic activity) or a no-exercise control condition. Participants in both groups completed a battery of computer-based cognitive tasks lasting approximately 90 minutes.

Participants

A total of 236 individuals, ranging in age from 6 to 25 years (*M* = 15.4, *SD* = 4.8), participated in this study. Children were recruited through the Child Study Center's database at the University of Massachusetts Amherst and an after school program at the YMCA of Greater Springfield. Undergraduate students at the University of Massachusetts Amherst were recruited on-line via the University's psychology research participation system. As compensation for taking part in the study, children received $10 and undergraduates received course credit.

Procedure

Participants were invited to either the University of Massachusetts Child Study Center or the YMCA of Greater Springfield. Informed consent was obtained from all individuals 18 years and older. Assent was obtained from children as well as informed consent from each child's legal guardian. Guardians completed a questionnaire with information on health history, family characteristics, and typical daily habits, including exercise and sleep routines (see Appendix A). Undergraduates completed a questionnaire on daily habits; including exercise and sleep (see Appendix B).

Experimenters determined each participant's height with a vertical tape measure attached to the wall and weight with an electronic scale. Using these measurements, Body Mass Index (BMI) was calculated for each participant. Blood pressure and heart rate (HR) were determined by an automated arm cuff system (Omron BP742 model; Omron Healthcare Inc., 2010).

For the exercise group, blood pressure and resting HR measures were taken before a 30-minute bout of moderate-intensity exercise on an elliptical trainer. Age and resting HR were used to estimate a maximum target HR for each participant (using the Karvonen formula; Karvonen, Kentala, & Mustala, 1957). A HR monitor was worn during exercise to ensure that HR stayed within each participant's target range (60-80% of maximum) for the middle 20 minutes of the 30-minute interval. The first and last five minutes of exercise were warm up and cool down periods, respectively. Upon completion of exercise, participants performed the battery of cognitive tasks, including the visuo-spatial working memory paradigm. Heart rate was also measured prior to, midway through, and after the task battery.

Individuals in the control condition did not exercise prior to engaging in the battery of tasks. Following completion of the experimental session, participants in both groups were debriefed, compensated, and thanked for their time.

Visuo-Spatial Working Memory Paradigm

A computerized N-back task, designed to measure visuo-spatial working memory, was presented as “the burglar game” and included an image of a burglar that appeared at various locations on the computer screen. The goal of the burglar game was for participants to determine if the burglar appeared in the same spatial location as two trials before the current trial (2-back). An example of the task stimuli is presented in Figure 1.

A small black fixation cross was presented in the center of the screen throughout an entire block of the task. Each trial consisted of a stimulus presented for 2000 ms, or until a response was made, and a 1500 ms inter-stimulus interval. Holding the computer mouse in their hands, similar to a video-game controller, participants responded using their thumbs to press the left or right button. Responses with the feet were made via custom designed response pedals that were spring loaded to bounce back similar to the computer mouse.

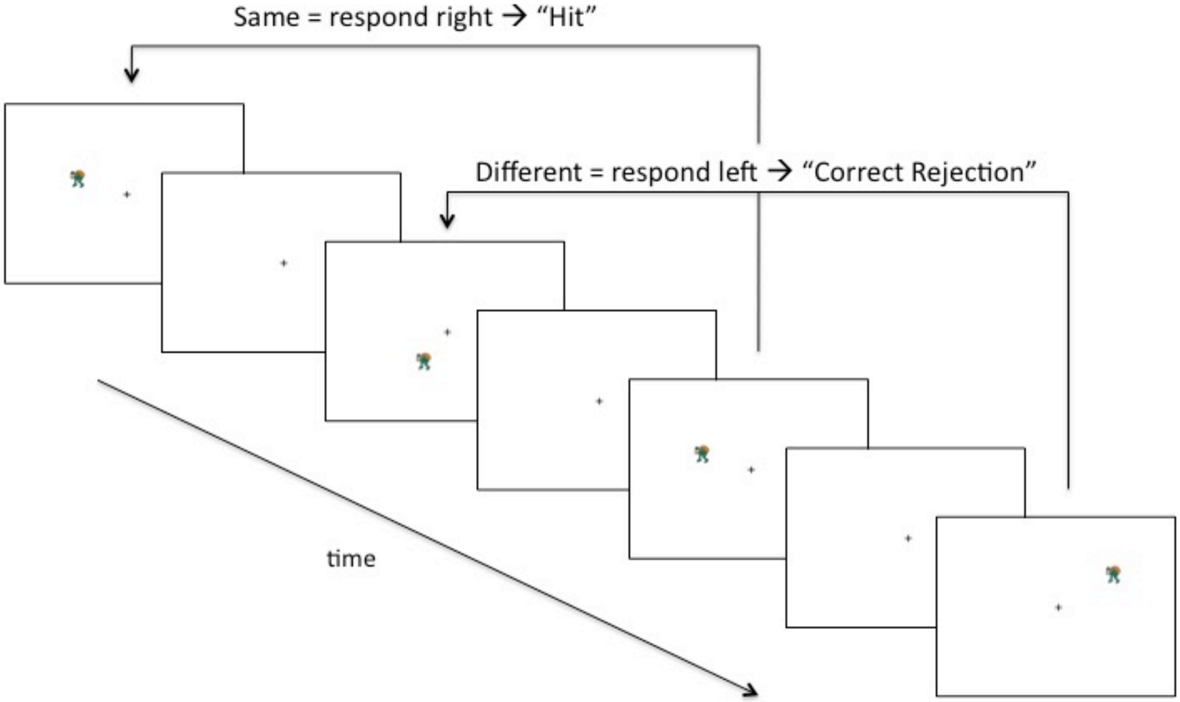
The task in the current study required a response on all trials. This ensured that participants were engaged and on task throughout the experiment. Many previous studies assessing working memory have used a version of the N-back task requiring participants to respond only on target trials (e.g., Cohen et al., 1994; Kwon, Reiss, & Menon, 2002). The design of the present paradigm allowed for multiple measures of working memory within a single task.

The experimenter instructed participants to “catch the burglar when he returns to the scene of the crime” and to respond with the right button when the burglar was in the same location as two trials before and the left button when he was in a different location. Correct responses within the 2000 ms time window were followed by a pleasant ding to reinforce game rules and keep participants on track. Incorrect responses or responses past 2000 ms were not accompanied by feedback.

A 15-trial practice block was followed by four 32-trial testing blocks. Blocks 1 and 3 included 12 target trials and blocks 2 and 4 included 13 target trials. Target trials were those in which the burglar appeared in the same location as two trials prior. Correct responses on target trials were considered “hits” and incorrect responses were “misses.” The remaining trials were nontarget trials in which the burglar was in a different location as two trials prior. Correct responses on nontarget trials resulted in “correct rejections” and incorrect responses were considered “false alarms.” Participants responded with their hands for blocks 1 and 3 and with their feet for blocks 2 and 4. All responses were recorded and correct responses, hits and correct rejections, were used in the present analyses.

Figure 1. Diagram of the Burglar game

Participants were instructed to respond on the right when the burglar was in the same spatial location as two trials before the current one and on the left when he was in a different location. Correct responses on each of these trials result in a hit and a correct rejection, respectively. Accuracy and RT data were recorded for all trials.



CHAPTER III

RESULTS

Analytic Strategy

Working memory performance was evaluated by four dependent variables: hit accuracy, hit RT, correct rejection accuracy, and correct rejection RT. Hit accuracy was measured as the percentage of correct responses on target trials where the burglar was in the same location. Hit RT was the average RT on all correct target trials. Correct rejection accuracy was measured as the percentage of trials in which participants correctly responded when the burglar was in a different location. Correct rejection RT was taken as the average RT on all such nontarget trials. Analyses were performed using SAS software (version 8.0; SAS Institute Inc., 1999) and SPSS Statistics for Windows software (version 20.0; IBM Corp., 2011). An alpha level of .05 was used to indicate statistical significance.

Exclusion Criteria

Prior to running analyses, each block of data was assessed for average accuracy performance on hit trials and on correct rejection trials. In order to ensure that participants were performing the task consistently, blocks of data with less than 50% accuracy on either the hit or correct rejection variable were eliminated. Participants with fewer than two acceptable blocks of data were excluded from analyses.

Participant Characteristics

Based on the exclusion criteria, the present analyses included 105 participants from the exercise condition and 88 control participants who did not exercise. Table 1 displays a breakdown of the 193 participants by experimental condition and gender. Average participant age did not differ significantly by condition (t (191) = .465, p > .05) or gender (t (191) = -.339, p > .05; see Table 2).

The majority of participants in the present study were Caucasian (76.1%). Table 3 displays the percentage of represented ethnicities of participants in each experimental condition. Answers to a survey question on socioeconomic status (SES) were collected from guardians of the child participants only. Table 4 displays SES according to family income for participants under 18 years old.

Average working memory performance as measured by the four dependent variables for all participants, regardless of age, condition, and gender, can be seen in Table 5. Hit trials proved to be more difficult than correct rejection trials, as was expected. Average performance on hit trials was 74.4% correct and average RT on these trials was 729 ms. Average performance on correct rejection trials was 87.7% correct and average RT was 726 ms.

Table 1. Number of Participants by Gender and Condition

Gender	*Exercise*	*Control*	*Total*
Male	55	53	108
Female	50	35	85
Total	105	88	

Table 2. Mean Age and Standard Deviation (in years) by Gender and Condition

Gender	*Exercise*	*Control*	*Total*
Male	16.3 (4.6)	15.7 (4.6)	16.0 (4.6)
Female	15.6 (4.5)	17.1 (4.3)	16.3 (4.5)
Total	15.9 (4.5)	16.3 (4.5)	

Table 3. Ethnicity by Condition

Ethnicity	*Exercise*	*Control*	*Percent*
White	82	65	76.1
Black	1	1	1.0
Hispanic	8	3	5.7
Asian	12	9	10.8
Native American	1	3	2.0
No response	1	7	4.1
Total	105	88	

Table 4. Children's Socioeconomic Status by Condition

Annual Income	*Exercise*	*Control*	*Percent*
$0-25,000	1	1	2.0
$25,000-50,000	4	4	8.1
$50,000-75,000	10	14	24.2
$75,000-100,000	13	9	22.2
>$100,000	20	14	34.3
No response	8	1	9.1
Total	56	43	

Table 5. Descriptive Statistics for Dependent Variables

	Mean	SD	Min	Max
Hit Accuracy	.744	.119	.52	1.00
Correct Rejection Accuracy	.877	.114	.53	1.00
Hit RT (ms)	729.19	181.95	370.57	1283.47
Correct Rejection RT (ms)	726.29	161.13	404.37	1221.65

Working Memory across Development

To identify the developmental trajectory of working memory, the data were collapsed to assess all participants independent of the exercise manipulation. Polynomial regression analyses were used to examine the quadratic relationship between each of the dependent measures and age. A curvilinear trajectory was found for both measures of RT. Correct rejection RT decreased with age ($\beta = 2.206$, $SE = .574$, p <.001), reaching peak performance at age 20.2 years[1] (see Figure 2). A significant negative relationship was

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[1] The formula for calculating peak performance in a quadratic model is –b1/2*b2.

found between hit RT and age (β = 2.928 *SE* = .636, p <.001), with peak performance occurring at 19.6 years, as seen in Figure 3. The accuracy measures showed different developmental trajectories. A significant quadratic term revealed that correct rejection accuracy improved with age (β = -.001, *SE* = .001, p = .024) and reached peak performance at 22.0 years, as seen in Figure 4. A quadratic effect was not present for hit accuracy, and thus a linear model was retained. Results showed a significant positive relationship between hit accuracy and age (β = .011, *SE* = .002, p < .001), as seen in Figure 5. Although a curvilinear trajectory was predicted for all of the dependent variables, the linear finding for the hit accuracy variable is not surprising given the difficulty of target trials.

Figure 2. Correct Rejection RT by Age

Correct rejection RT decreased with age, reaching peak performance at 20.2 years.

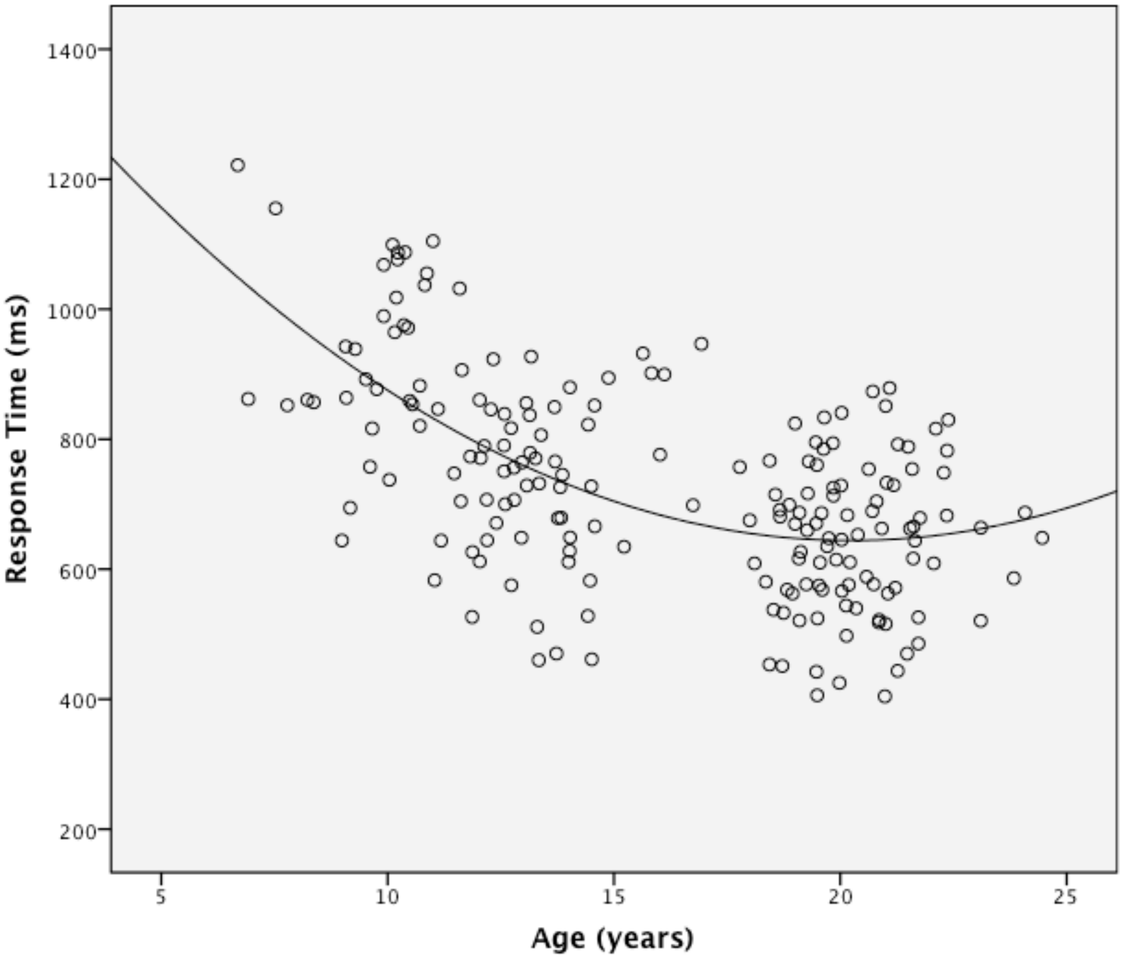


Figure 3. Hit RT by Age

Hit RT decreased with age, reaching peak performance at 19.6 years.

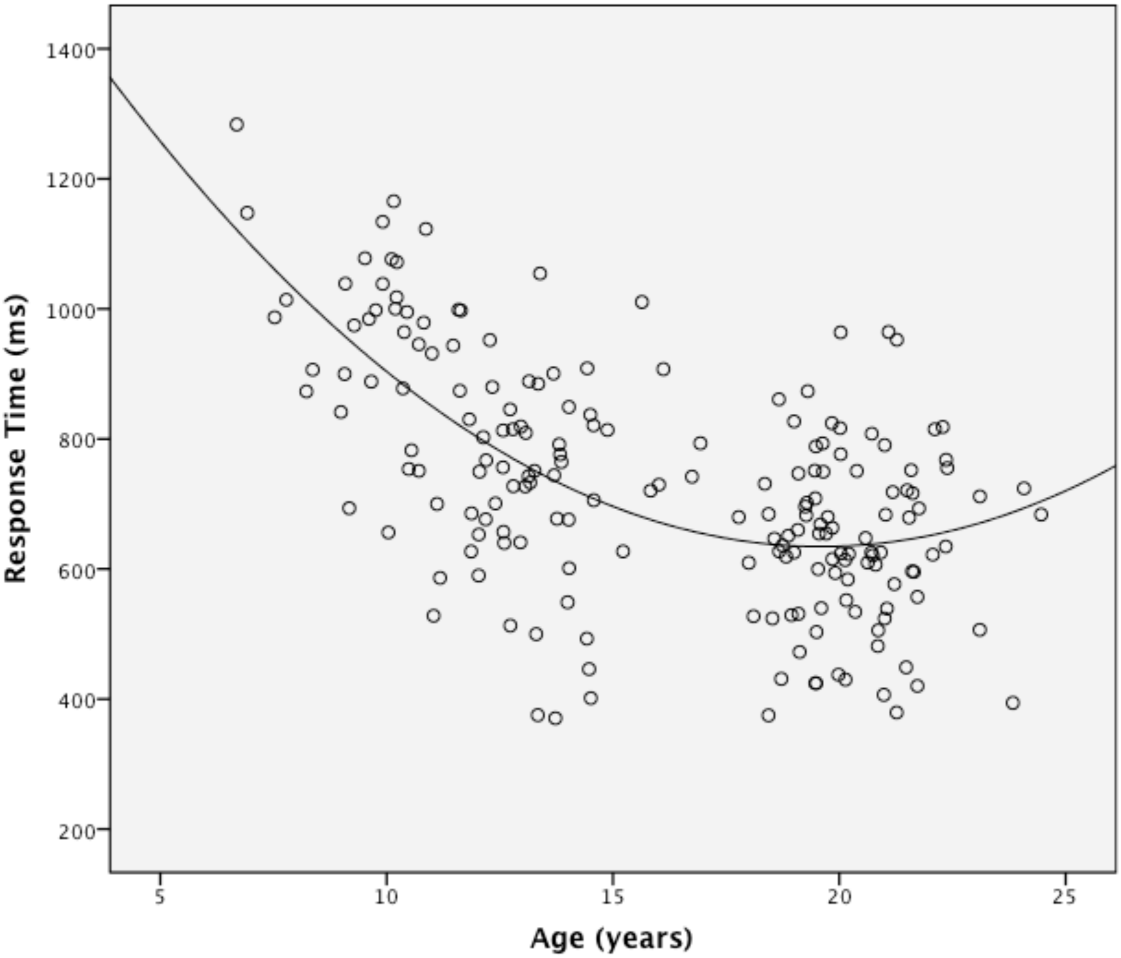


Figure 4. Correct Rejection Accuracy by Age

Correct rejection accuracy improved age, reaching peak performance at 22.0 years.

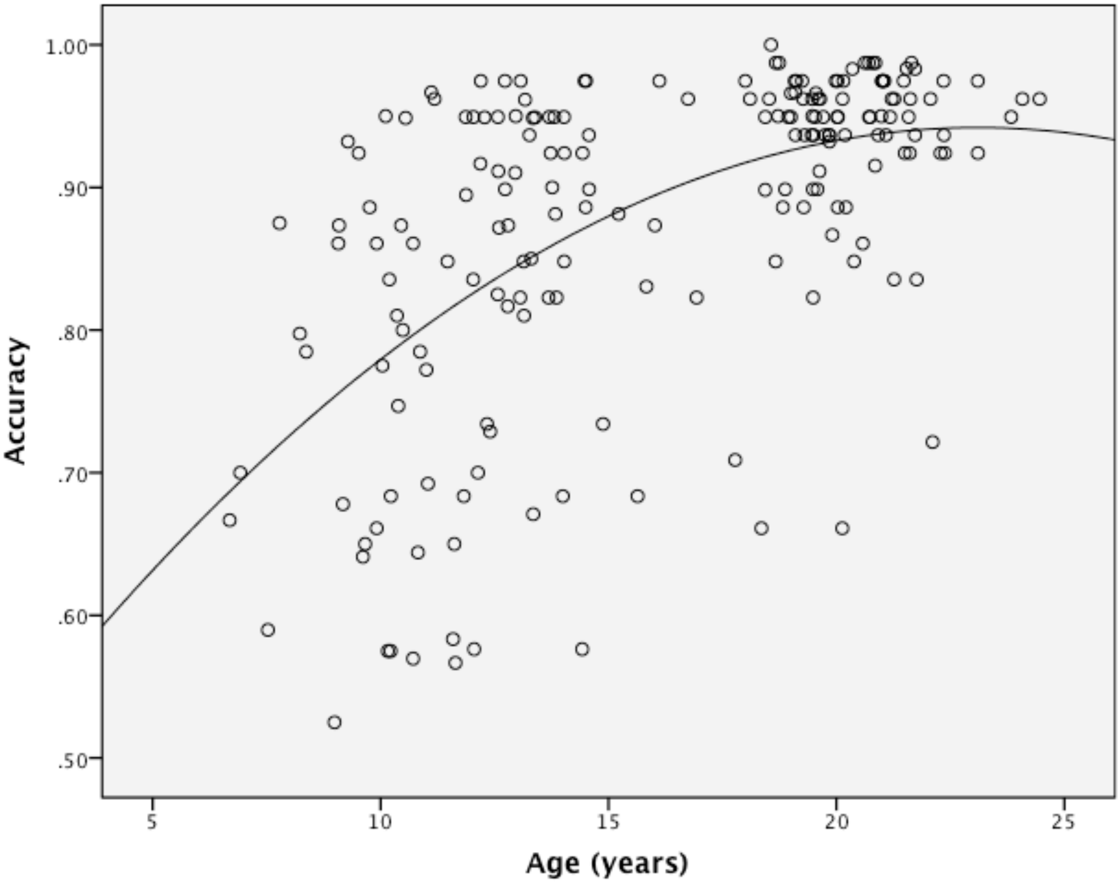
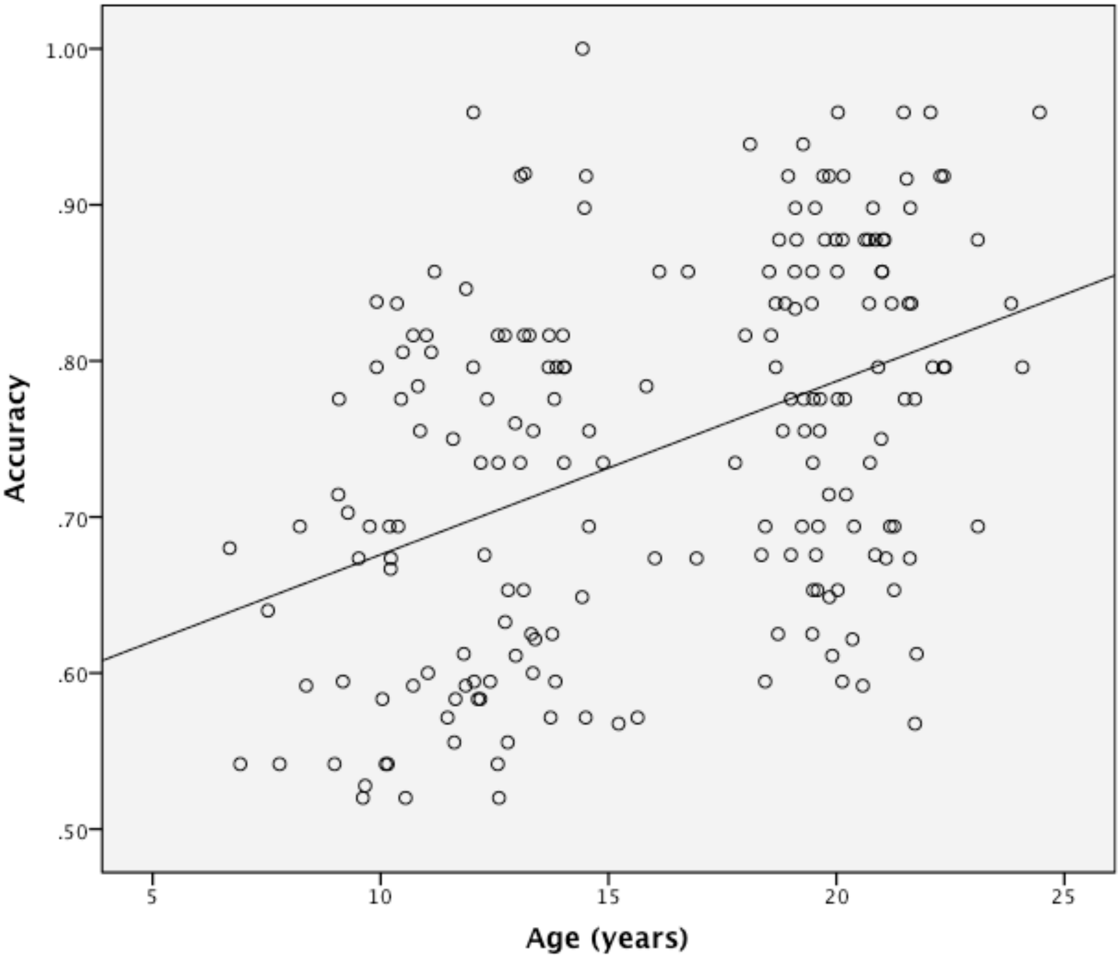


Figure 5. Hit Accuracy by Age

Hit accuracy improved linearly with age.



The Influence of Acute Exercise on Working Memory

Each of the dependent variables in the present study was a measure of the same underlying construct: working memory ability. Rather than using each variable individually to assess working memory performance following acute exercise, a more powerful test would examine all of the variables together (Bray & Maxwell, 1985). A multivariate approach takes into account the shared-variance relationship that univariate analyses, such as analysis of variance (ANOVA), does not. Thus, multivariate analysis of covariance (MANCOVA) was used to determine if there were differences in working memory performance across condition and gender, while controlling for age.

No main effects of condition were found on any of the dependent variables in this multivariate analysis. Performance on hit trials did not differ between the exercise and control conditions in terms of accuracy (F (1, 188) = .934, $p > .05$) or RT (F (1, 188) = .923, $p > .05$). Correct rejection performance also did not differ between condition as measured by accuracy (F (1, 188) = .121, $p > .05$) or RT (F (1, 188) = 2.43, $p > .05$).

There was no main effect of gender on hit accuracy (F (1, 188) = .211, $p > .05$). A marginally significant effect was seen for gender on the hit RT variable (F (1, 188) = 3.86, $p = .051$). Females were slower, on average, to respond on hit trials (M = 750.94, SE = 163.82 ms) than males (M = 712.06, SE = 194.07 ms). This marginal finding is in line with research suggesting that females have more difficulty than males on visuo-spatial tasks requiring the active manipulation of information (Vecchi & Girelli, 1998). Performance on correct rejection trials did not differ by gender in accuracy (F (1, 188) = .527, $p > .05$) or RT (F (1, 188) = 2.50, $p > .05$).

There were no condition by gender interaction effects on any of the dependent variables. Hit trial performance did not show a condition by gender interaction for accuracy (*F* (1, 188) = .360, *p* > .05) or RT (*F* (1, 188) = .227, *p* > .05). Correct rejection trial performance also did not reveal a condition by gender interaction for accuracy (*F* (1, 188) = .001, *p* > .05) or RT (*F* (1, 188) = .024, *p* > .05). Average performance by condition and gender is shown in Table 6.

Table 6. Descriptive Statistics for Dependent Variables by Condition and Gender

	Exercise		Control	
	Mean	SD	Mean	SD
Hit Accuracy				
Female	.745	.109	.756	.126
Male	.755	.128	.724	.115
Correct Rejection Accuracy				
Female	.873	.096	.899	.111
Male	.873	.124	.869	.122
Hit RT (ms)				
Female	769.25	157.80	724.79	170.94
Male	721.30	185.62	702.47	203.79
Correct Rejection RT (ms)				
Female	765.78	160.63	708.74	162.72
Male	724.60	147.99	702.39	170.90

The Influence of Acute Exercise on Working Memory across Development

Given the results of the previous aim showing that acute exercise clearly did not influence working memory performance in the present sample, follow-up analyses to determine a potential differential influence of age were not necessary.

CHAPTER IV

DISCUSSION

Working memory is an executive function that develops throughout childhood and into adolescence (Gathercole, et al., 2004; Luciana, et al., 2005). The exact trajectory of the development of working memory ability has been suggested to depend upon the cognitive complexity of the task being assessed (Luciana, et al., 2005). Results from the present study showed different developmental trajectories for correct rejection trials and hit trials, supporting this notion of task dependency in working memory performance across development. Additionally, various forms of training have led to improvements in working memory performance (Morrison & Chein, 2011), including physical activity (Pontifex, et al., 2009; Sibley & Beilock, 2007). Using an experimental design, the present study did not find an effect of acute exercise on working memory performance. This null finding may be a result of limitations of the current study, as discussed below.

Working Memory across Development

The present study sought to identify the developmental trajectory of working memory as indexed by performance on a visuo-spatial N-back task. Previous research shows that increased working memory load is associated with a decrease in performance, as measured by accuracy (Callicott et al., 1999). The target trials in the current study were more difficult than nontarget trials, as seen in the average accuracy scores (74.4% versus 87.7%, respectively). Working memory performance has been shown to be task dependent, such that tasks requiring a greater degree of cognitive control show later development than tasks requiring less control (Luciana, et al., 2005). Although the present study used only one task, the two types of trials showed differing levels of cognitive difficulty. Given the difficulty of target trials relative to nontarget trials, it makes sense that the developmental trajectory would differ between the two trial types. Accuracy performance on nontarget trials showed curvilinear improvement with age, with peak performance occurring at 22.0 years (Figure 4). Accuracy performance on target trials, which are more cognitively taxing, showed linear improvement with age (Figure 5). Peak performance, as measured by accuracy, was not captured on target trials in the present sample; perhaps broadening the sample to age 30 or 35 years would allow for this. It may also be possible that the present sample did not include enough older participants, and simply collecting data from more 20 to 25 year olds would allow for the peak of performance to be captured.

Previous neuroimaging studies in adults have identified regions of the brain that are involved in visuo-spatial working memory processing (e.g., Smith & Jonides, 1998). The prefrontal cortex is associated with the control mechanisms involved in working memory, whereas the posterior parietal cortex is associated with spatial rehearsal involved in visuo-spatial working memory tasks. Kwon, Reiss, and Menon (2002) used neuroimaging to assess visuo-spatial working memory from a developmental perspective. An N-back task was used to evaluate the neural basis of visuo-spatial working memory in a small sample of 7 to 22 year olds using functional MRI. Results showed age-related improvements in working memory performance that coincided with increased activation in the prefrontal cortex and posterior parietal cortex, the same regions found previously to be involved in visuo-spatial working memory in adults (e.g., Smith & Jonides, 1998). Additionally, a positive correlation was found between the development of working memory ability and white matter connectivity, as measured by fractional anisotrophy, between the frontal and parietal cortices (Nagy, Westerberg, & Klingberg, 2004).

These regions of the brain continue to show anatomical changes throughout childhood and into early adulthood (Gogtay et al., 2004). A key structural change that continues during this developmental time period is gray matter maturation, which occurs in a parietal-to-frontal direction. Considering the Baddeley and Hitch working memory model (Baddeley, 2000, 2003; Baddeley & Hitch, 1974), it seems that the visuo-spatial sketchpad, which has been associated with activity in the posterior parietal region of the brain, would reach peak development prior to the central executive, which is associated with activity in the prefrontal region. Two components of these structural changes include gray matter loss that is likely the result of synaptic pruning (e.g., Giedd et al., 1999) and white matter maturation resulting from myelination of axons (e.g., Benes, 1989). There is evidence to suggest that the peak of synaptic pruning occurs between puberty and early adulthood (de Graaf-Peters & Hadders-Algra, 2006) and axon myelination continues into adulthood (e.g., Benes, 1989; Huppi & Dubois, 2006). This developmental timing is in line with the behavioral results from the present study. Speed of response on correct rejection trials peaked at 20.2 years (Figure 2) and hit trial RT peaked at 19.6 years (Figure 3). Peak accuracy performance on correct rejection trials occurred at 22.0 years (Figure 4), whereas peak accuracy performance on hit trials was not captured in the current sample (Figure 5). Brain regions found to support visuo-spatial working memory tasks continue developing into early adulthood (Gogtay, et al., 2004), and the behavioral results of the present study coincide with these anatomical changes.

The Influence of Acute Exercise on Working Memory

Although acute exercise has been shown to improve working memory performance in adults (Pontifex, et al., 2009; Sibley & Beilock, 2007), results of the present study did not support this effect across a developmental sample. Participants in the exercise group did not show better accuracy or faster RT than those in the control condition on the visuo-spatial N-back task. The exercise manipulation employed in the current study may not have been long enough or vigorous enough to elicit a difference in working memory performance between those participants who engaged in exercise and those that did not. Although 30 minutes of moderate-intensity exercise has shown to elicit a variety of cognitive benefits (e.g., Tomporowski, 2003), including working memory improvement (Pontifex, et al., 2009; Sibley & Beilock, 2007), it did not influence performance on the present task. As discussed, the visuo-spatial working memory task was cognitively demanding, perhaps necessitating an increase in duration or intensity of exercise for an influence to be observed.

The lack of an exercise effect in the present study may have been because the control condition did not include a sedentary period prior to the working memory task. Like the present study, Sibley and Beilock (2007) did not use a sedentary period in their control condition and still found that acute exercise influenced working memory performance for a subgroup of their sample. However, Pontifex and colleagues (2009) included 30 minutes of seated rest as a control. Perhaps a difference in working memory performance would have been detected in the present study if the control group engaged in a sedentary activity, such as seated rest, prior to engaging in the task.

The current study included a large number of individuals who were randomly assigned to an exercise condition or a control condition. This experimental design should have been sufficient to detect an influence of acute exercise on performance of the present working memory task if one existed. It is possible, however, that working memory may not be as susceptible to acute exercise as some other executive functions. Literature addressing this research question may be limited because few researchers have been able to detect differences in working memory performance following an acute bout of exercise.

The Influence of Acute Exercise on Working Memory across Development

The present study sought to identify a possible link between acute exercise and working memory performance from a developmental perspective. Since acute exercise was found to exert an influence on adults with lower pre-existing working memory abilities (Sibley & Beilock, 2007), it was hypothesized that acute exercise would influence working memory performance in children, whose working memory abilities are not fully developed. However, the current study detected no such influence.

Gender Difference in Visuo-Spatial Working Memory

Previous research shows that males and females differ in their visuo-spatial working memory abilities, particularly when it comes to actively processing visuo-spatial information (Vecchi & Girelli, 1998). Using tasks that involved active and passive manipulation of visuo-spatial information, Vecchi & Girelli (1998) found that females had more difficulty than males on tasks involving active processing. In line with this finding, the present study found a marginal effect for gender on the hit RT measure (*p* = .051). Females were slower, on average (750.94 ms), to respond on target trials than males (712.06 ms).

Study Limitations and Future Directions

There were several limitations to the present study. Although a broader age range was tested than in previous studies exploring the development of working memory, this study would have benefitted from using several working memory tasks. Gathercole and colleagues (2004) employed a variety of tasks to tap into subcomponents of working memory, but found no difference in developmental trajectories among these components, likely because the tasks were difficult and they only tested participants to age 15 years. Peak performance on these tasks likely occurs later and it would be interesting to use the same tasks in an older sample to determine if the subcomponents of working memory truly develop at the same pace. Based on the nature of brain development discussed earlier, I predict that the visuo-spatial sketchpad develops earlier than the central executive, but occurs later than age 15 years. Therefore, Gathercole and colleagues (2004) were not able to detect a developmental difference between these working memory components. The present task required the central executive and visuo-spatial sketchpad; however, these components of working memory could not be assessed separately in the single task. Additionally, using several tasks varying in their demand for cognitive control, similar to Luciana and colleagues (2005), would allow for a more thorough investigation of working memory development into adulthood.

Results from the present study revealed a bimodal distribution of age, with few participants between the ages of 14 and 18 years. Although this bimodal distribution likely would not influence the nature of the regressions, it may have influenced the age of peak performance on each of the dependent variables. Additional data collection to fill in this adolescent age gap would be beneficial to ensure that the developmental trajectories of the study sample are reflective of the population.

As mentioned, results of the present study may have differed if a longer or more vigorous bout of exercise had been incorporated. Inclusion of a sedentary activity, such as seated rest, for the control group may also have led to different results. Lastly, the present study was part of a larger project assessing the influence of acute exercise on several cognitive measures. The present paradigm was tested second in the battery of tasks, after a switching paradigm designed to test cognitive flexibility. The switching task took approximately 20 minutes and may have adversely influenced performance on the present visuo-spatial N-back task. Although Pontifex and colleagues (2009) found that acute exercise led to faster RT on a working memory task 30 minutes after physical activity occurred, the delay between exercise completion and the onset of the working memory task in the current study may have influenced the results.

Though not the focus of this thesis, additional measures were collected from participants that could be used in future analyses to address slightly different research questions (see Appendix A for children and Appendix B for adults). Physical activity may only be influential on cognitive performance for certain individuals. For example, Davis and colleagues (2011) found that overweight children improved on a cognitive assessment following a physical activity program. Future analyses of the present data could use BMI to identify overweight individuals, and may determine that they are more susceptible to an influence of acute exercise than are normal weight individuals.

Increased activation in working memory-related areas of the brain have been found following working memory training (Olesen, Westerberg, & Klingberg, 2004), suggesting a potential for plasticity. This research, coupled with the present study's finding that working memory continues to develop into early adulthood, suggests a long window of opportunity to alter working memory performance. Although the present study did not see an influence of acute exercise on the current visuo-spatial working memory task, similar interventions that have the potential to improve working memory performance should continue to be explored.

APPENDIX A

PARENT QUESTIONNAIRE

Your answers are confidential and you have the right to decline to provide any or all of this info.

Subject # __________ DOB ________________
Date__________________

Sex ___________ Ethnicity ________________ First Language__________

Full-Term Baby?:_______ Complications? ____

Number of Siblings?______ Ages: ___________________ Genders: ________________

Current Age? Mother:__________ Father:__________

Age at Birth? Mother:__________ Father:__________

Education? Mother:__________ Father:__________

Occupation? Mother:__________ Father:__________

Annual Family Income: 0-25_____ 25-50_____ 50-75_____ 75-100_____ >100____

Grades in School: As____ As&Bs____ Bs____ Bs&Cs___ Cs____ Cs&Ds____ Ds____

Does your child take any medications? ____

Does your child have any allergies? ____

In the past week estimate the number of hours has your child spent in the following activities:

		Average?
Physically Active?	_____________	_____________

Watching TV?	______________	______________
Video Games?	______________	______________
Sleeping?	______________	______________

What types of activities?

____

What types of video games?

____

Play any organized sports?

____

Play any musical
instruments?____

Have any other hobbies?

____

APPENDIX B

SELF REPORT QUESTIONNAIRE

The experimenter will not see your responses to this questionnaire and your identity will remain private. Please place this questionnaire in the envelope in front of you when you are finished. Thank you very much!

For the *past week* Is this more or less OR What is
average
please estimate: than average for you? for
you?
(write more or less) (number of
hours)

The amount of hours you spent
exercising this week? __________ ______________
____

The amount of hours you
spent watching TV this week?__________ ______________
____

The of hours you spent this
week playing video games? __________ ______________
____

The average amount of hours
of sleep you got per night this
week? __________ ______________
____

What types of exercise?

____

____

What types of video games?

____

____

Do you play any sports?

____

____

Do you play any
instruments?____

____

Do you have any hobbies?
____

Do you drive a car? ___________ Standard or Automatic? How Long?
____

For **Female** Subjects only:

1. What was the first day of your last period? _________________
2. Are you currently using synthetic hormones to regulate your cycle (e.g. the pill, Nuvaring, IUDs etc.)? Yes / No
3. In the past three months have you used synthetic hormone regulation? Yes / No
4. If you answered yes to either questions 2 or 3 please indicate how long since you have been or stopped using synthetic regulators. _______________

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