ABSTRACT

Title of Thesis: INVESTIGATION OF COGNITIVE AND LINGUISTIC EFFECTS OF EXERCISE ON OLDER ADULTS

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This study examines the effect of a single session of exercise on response speed, inhibitory control, and lexical processing in older adults. A prior study in college-aged adults found faster responses in domain general processing and lexical recognition after exercise, but not in inhibitory control or lexical retrieval. We hypothesized older adults would show a greater exercise benefit with slower overall response times. This study found that, relative to a sedentary control condition, there were no changes in any experimental condition. Older adults showed practice effects in the exercise and control conditions. This study shows the effects of acute exercise in older adults are negligible compared to those in younger adults, at least in the paradigm used in this study. Findings highlight the importance of using a control task and are consistent with meta-analyses that highlight small effect sizes associated with acute exercise and the role of other mediating variables.

INVESTIGATION OF COGNITIVE AND LINGUISTIC EFFECTS OF EXERCISE ON OLDER ADULTS

by

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Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

Over the years, the literature has grown regarding the positive effects of exercise on the physical and psychological health of the general public (Zoeller, 2007; Manca, 2006). Furthermore, research has shown that exercise in various forms may be an effective catalyst in the prevention and rehabilitation of various cognitive ailments (Manca, 2006; Marzolini, Oh, Mcllroy, & Brooks, 2012). Research regarding the effects of exercise has been conducted on neurologically healthy adults (Kramer & Colcombe, 2018) as well as individuals with cognitive deficits resulting from brain injury (Rand, Eng, Liu-Ambrose, & Tawashy, 2010; Ploughman, McCarthy, Bossé, Sullivan, & Bkin, 2008). Likewise, the effects of different forms and dosage of exercise, such as stretching versus cardiovascular exercise, acute exercise at one point in time, and chronic exercise completed over prolonged time periods, have been examined (Marzolini et al., 2012; Rand et al., 2010; Ploughman et al., 2008).

Less is known regarding the effects of single bouts of acute exercise, as most research has been conducted to evaluate the effects of chronic physical training. However, the ephemeral nature of acute exercise has particular clinical value, as any cognitive and linguistic effects of exercise could potentially be beneficial as a short-term facilitator prior to cognitive and linguistic training. Overall, acute exercise has shown a small positive effect on cognition (Chang et al., 2012; Lambourne & Tomporowski, 2010; Etnier et al., 1997). Cognitive effects, when present, have been determined to last up to two hours after exercise, indicating the potential for a feasible timeframe for intervention (Chang, Labban, Gapin, & Etnier, 2012). Furthermore, no research has been published regarding linguistic implications of exercise, indicating a need for further exploration of effects.

In addition to dosage, age may play a role in the cognitive effects of exercise, as age-related decline in cognition and inhibitory control has been documented (Boucard et al., 2012). Specifically, age has been shown to impact functional connectivity of frontal networks, as evidenced by reduced lateralization during completion of various cognitive tasks in older adults as compared to younger adults (Cabeza, 2002). Furthermore, some studies have shown that chronic exercise improves executive performance through improved performance on tasks of executive functioning in older adults, but not in younger adults (Boucard et al., 2012; Hillman, Kramer, Belopolsky, & Smith, 2006). In terms of language, age-related changes in linguistic processing have been documented (Thornton & Light, 2006), indicating that in addition to cognitive effects, age could impact linguistic effects of exercise. This project examines the effect of acute exercise on measures of domain-general inhibitory control and language, specifically word retrieval and word recognition, in order to better understand the neural mechanisms underlying acute exercise; the two most prominent theories of which will be discussed in detail.

The mechanism(s) behind the cognitive effects of exercise are widely unknown. Two such possibilities that were explored in this study include an increase in arousal (Tomporowski & Ellis, 1986) or connectivity of inhibitory networks (Lambourne & Tomporowski, 2010). Arousal is said to improve neural conduction and hence processing speed, which declines with age (Tomporowski & Ellis, 1986;

Salthouse, 1996), whereas increased inhibitory connectivity could improve inhibitory control, which also declines with age (Lambourne & Tomporowski, 2010; Dempster, 1992). Because language production is a speeded cognitive process which relies on arousal and inhibitory control, enhancing these mechanisms through exercise may result in linguistic benefits, with greater effect for older adults.

Faroqi-Shah, Fuchs, and Powers (in prep) conducted a study that examined the effects of an acute exercise regimen on cognition and language in neurologically healthy college-aged adults. Specifically, domain-general cognitive and language processes were evaluated in terms of speed and inhibitory control after 25-minutes of cycling using a 2x2 design. Results indicated significant improvements in speed of both the cognitive and linguistic tasks as measured by general processing speed and lexical decision, respectively. Inhibitory measures of cognition (Stroop task) and language (word retrieval) did not significantly improve after exercise. Therefore, findings support the arousal theory of exercise (Tomporowski & Ellis, 1986; Faroqi-Shah et al., in prep).

The goal of this study is to determine if these effects are replicated, or increased (i.e., inhibitory effects not seen in young adults may be seen in this population), in older adults due to influence of age-related cognitive and linguistic changes. In the following sections, the cognitive and linguistic effects of exercise on healthy adults, the relationship between exercise and aging, the mechanisms by which exercise may impact cognition and language, and characteristics of language in aging, will be discussed.

Chapter 2: Literature Review

Mechanisms by Which Exercise Impacts Cognition

The mechanism(s) by which physical exercise improves cognitive and motor performance remains debated among researchers. Some suggest exercise improves general speed or skill acquisition through increased arousal (Tomporowski & Ellis, 1986), others point to visuospatial processing, and still others suggest a general improvement in executive functioning, possibly due to increased connectivity of inhibitory pathways (Lambourne & Tomporowski, 2010). A combination of influences from each of these or other hypotheses is also plausible (Colcombe & Kramer, 2003).

Some speculate that exercise improves cognitive and motor function through general improvement in processing speed, known as the *speed hypothesis*. The underlying theory behind the speed hypothesis is thought to involve release of neurotransmitters, specifically catecholamines, as a result of exercise that increase brain activity and potentially quicken general processing speed (McMorris, Sproule, Turner, & Hale, 2011). This hypothesis has implications for language and will be discussed in further detail in a later section (Kramer & Colcombe, 2018).

In addition to behavioral measures, studies have also reported structural and functional neural changes, some of which will be briefly discussed. To date, these changes have been predominantly explored in terms of the long-term effects of chronic exercise. The most significant of these involve structural (e.g., brain volume) and functional (e.g., improved connectivity) changes in the prefrontal cortex, which are consistent with behavioral improvements in attention, inhibition, planning, and working memory (Kramer & Colcombe, 2018; Basso & Suzuki, 2017; Ratey & Loher, 2011).

Recent evidence supports the notion that acute exercise also induces neuroplastic changes that could be harnessed during rehabilitation, such as increased hippocampal connectivity (Voss et al., 2019), increased activation of the dorsolateral prefrontal cortex (Chu, Alderman, Wei, & Chang, 2015), and increased concentration of brain-derived neurotrophic factor (BDNF) in the hippocampal region (Griffin et al., 2011). BDNF is a protein that has been linked to improvements in neuronal health and function. This enhanced connectivity is thought to contribute to improvements in human cognitive abilities, such as processing speed (Dinoff, Hermann, Swardfager, & Lanctôt, 2017). Increases in BDNF as a result of acute exercise have been correlated to improved memory and attention (i.e., face-name matching), but not inhibitory control (i.e., Stroop effect) (Griffin et al., 2011). However, these findings have not been consistently replicated (Ferris, Williams, & Shen, 2017), and further research is warranted in order to determine the specific cognitive benefits of increased BDNF. These changes are especially relevant to the older adult population, as even healthy agers experience some level of cognitive decline (via neurodegeneration), and others experience clinical levels of neurodegeneration in conditions such as Parkinson's disease and dementia (Basso & Suzuki, 2017).

In summary, two possible mechanisms of exercise-induced cognitive changes explored in this study are arousal (Tomporowski & Ellis, 1986) and inhibition (Lambourne & Tomporowski, 2010). Neurobehavioral, neurostructural, and neurofunctional effects have been reported. In the following section, specific exercise effects in young adults will be discussed, with a specific focus on acute dosage.

Effects of Exercise on Cognition in Healthy Young Adults

Both acute and chronic exercise have shown to affect cognitive performance, with mixed results. In addition to positive effects (Chang et al., 2012; Kramer et al., 1999; Etnier et al., 1997), some studies have reported no change in cognitive behavioral performance as a result of acute or chronic exercise (Smiley-Oyen, Lowry, Francois, Kohut, & Ekkekakis, 2008; Etnier, Nowell, Landers, & Sibley 2006). Furthermore, some studies found a reduction in speed (i.e., increased reaction time) and inhibitory control (i.e., larger interference effect), and suggest that exercise may negatively impact cognitive performance as a result of fatigue (Lambourne & Tomporowski, 2010; Pontifex & Hillman, 2007; Ando et al., 2005).

Though the literature has predominantly focused on chronic exercise, a growing body of research suggests that acute exercise facilitates positive cognitive changes as well. As mentioned in the previous section, arousal theories will be supported if reaction time improves as a result of a bout of acute exercise. Three studies examined the effect of a single bout of acute exercise on processing speed (Rattray & Shmee, 2013; Davranche, Burle, Audiffren & Hasbroucq, 2006; McMorris & Keen, 1994). All studies used cycling. In two studies, improvements in reaction time were seen during (Davranche et al., 2006) and immediately after (Rattray & Shmee, 2013) a bout of acute exercise. Conversely, McMorris and Keen (1994) found that a single bout of maximal intensity cycling (cycling at 70-100% of VO_2max until the participant could no longer cycle at 70 pedals per minute) had a negative effect on reaction time. All studies included a sedentary control condition and used a within-subjects repeated measures design. In addition to measurement of reaction time at different points (i.e., during vs. after exercise), differences among studies regarding exercise intensity (and measure of intensity), exercise duration, or both may have contributed to contradictory results. Rattray and Shmee (2013) utilized ten minutes of moderately-intense cycling (90% max ventilatory threshold) cycling, while Davaranche et al. (2006) utilized fifteen minutes of moderate intensity (50% VO_2max) cycling, and McMorris and Keen (1994) utilized maximal intensity cycling to exhaustion (detailed above).

Improved inhibition theories will be supported by improvements on tasks evaluating inhibitory control, such as Stroop and flanker. One study found improved flanker performance as evidenced by smaller interference effect (incongruent minus congruent reaction time) as a result of thirty-minutes of treadmill walking (O'Leary, Pontifex, Scudder, Brown, & Hillman, 2011), indicating that inhibitory control improved as a result of a single bout of exercise. Conversely, two studies found no significant reduction in interference effect after an acute exercise protocol (Pontifex & Hillman, 2007; Themanson & Hillman, 2006) utilizing the flanker task. Furthermore, Pontifex & Hillman (2007) reported increased interference effect during self-paced steady-state cycling, indicating decreased inhibitory control as a result of exercise. All studies included a sedentary control condition and utilized a within-subjects repeated measures design.

Additionally, two studies found that acute treadmill exercise induced smaller interference effect, thus improving inhibitory control, in neurologically healthy adults using the Stroop task (Alves et al., 2012; Sibley, Etnier, & Le Masurier, 2006; also see Boucard et al., 2012). Both studies included a sedentary control condition and used a within-subjects repeated measures design. Alves et al. (2012) also found improvement in reaction time (speed) for both congruent and incongruent trials in the aerobic exercise condition compared to the control condition, indicating increased arousal in addition to improved inhibitory control.

Confounding variables such as small, nonrandomized control groups and use of within-subject rather than between-subject design, as well as the wide range of approaches and tasks utilized among researchers makes comparison of results and rationalization of discrepant results across studies difficult (Kramer & Colcombe, 2018; Lambourne & Tomporowski, 2010). For example, researchers utilize a variety of tasks to evaluate inhibitory control, such as trail-making tasks, Stroop, and flanker (Alves et al., 2012; Themanson & Hillman, 2006). If the same version of the task is used before and after exercise (e.g. the same words in the Stroop task), then one may risk observing a practice effect when participants perform the same experimental task twice within the same experimental session (e.g., before and after exercise). Hence it is important to closely examine studies to see if they used a matched control condition.

Differences among studies regarding acute aerobic exercise protocols may also complicate comparison of findings across studies. Some utilize treadmill tasks (Alves et al., 2012; Sibley, Etnier, & Le Masurier, 2006), and some cycling (Rattray & Shmee, 2013; Davranche, Burle, Audiffren & Hasbroucq, 2006). Some work at mid-intensity for a fixed time period (Davaranche et al., 2006; Sibley, Etnier, & Le

Masurier, 2006) while others instruct participants to work to exhaustion, thus exercise times differ among participants based on their level of physical fitness (Chang, Chu, Wang, Song & Wei, 2015; Morris & McKeen, 1994). Furthermore, some measure cognitive effects during exercise (Davranche et al., 2006) and some immediately after (Rattray & Shmee, 2013). In addition to methodological challenges, inability to differentiate between and accurately measure various domains of executive functioning (i.e., task impurity problem) provides a layer of difficulty in interpretation of findings (Pérez, Padilla, Parmentier, & Andrés, 2014).

Overall, acute exercise induces a small positive effect on cognitive performance in the healthy adult population, as supported by multiple meta-analyses (Chang et al., 2012; Lambourne & Tomporowski, 2010; Etnier et al., 1997). However, it is unclear which mechanism, inhibition, arousal, or another, is responsible for these changes. Hence, further research is needed. Methodological issues present in related studies reinforce this notion. In the next section, findings related to exercise-induced cognitive changes in older adults (50+) will be discussed.

Exercise and Aging

General cognitive slowing and changes in inhibitory control have been associated with normal aging (Boucard et al., 2012; Salthouse, 1996). Specifically, general efficiency and accuracy of reasoning skills, working memory, processing speed, and learning and recollection of new information have all shown mild decline, while implicit memory and vocabulary remain largely intact in healthy agers (Goh & Park, 2012). Studies have shown that exercise has induced small positive cognitive changes in older adults, though the majority of the literature focuses on chronic rather than acute exercise in this population, and evidence is mixed (Kramer & Colcombe, 2018; Kramer et al., 1999).

In fact, studies comparing old and young adult groups have reported larger cognitive effects in older adults than younger adults in terms of inhibition, coding, and task switching ability (Boucard et al., 2012; Stones & Kozma, 1986). A meta-analysis by Kramer and Colcombe (2018) focusing on older adults (55+) revealed that chronic aerobic exercise (6-months to 1-year of intervention) correlates with positive structural and functional brain changes in this population. Specifically, changes in brain volume along with improved performance on inhibitory control tasks were seen, indicating improved attention and functional connectivity.

Research exists regarding physiological changes with acute exercise in the older adult population as well. Increased connectivity (blood flow) has been reported in the hippocampal memory networks of older adults as a result of acute exercise (Voss et al., 2019). Additionally, increased activation of frontal executive control networks, and corresponding improvements in performance accuracy on a conflict monitoring task (i.e. flanker) have been reported (Won, Alfini, Weiss, Callow, & Smith, 2019a). Finally, improved semantic memory correlated to increased connectivity of the hippocampus, middle frontal gyrus, inferior and middle temporal gyri, and fusiform gyrus have been reported in this population as well (Won et al., 2019b). These may have implications for exercise effects on lexical processing, as both the frontal and temporal gyri have known linguistic functions (Price, Crinion, & MacSweeney, 2011).

Other studies point to the *speed hypothesis* as the mechanism by which exercise induces positive cognitive changes in older adults. Hillman et al., (2006) found that in both older and younger adults, increased cardiovascular fitness levels as a result of *chronic* aerobic exercise correlated with increased processing speed as measured by a task switching paradigm. Furthermore, Stones & Kozma (1989) found that spatial localization skills, as measured by accuracy and speed of performance on the Symbol Digit task, improved only in physically fit older adults (not in younger adults or inactive older adults). Although there is far less research on acute exercise in older adults, two studies found improved response time in the Stroop task following twenty-minutes of treadmill exercise (Barella, Etnier, & Chang, 2010) and cycling at VO_2max (time varied among participants based on individual fitness levels) (Chang, Chu, Wang, Song & Wei, 2014).

Two studies support the inhibitory control mechanism of exercise in older adults. Won et al. (2019b) reported improved performance accuracy, but not improved reaction time, on the flanker task after thirty minutes of cycling. Boucard et al. (2012), noted improvements in inhibitory control measured by the Stroop effect in older adults, but not younger adults as a result of chronic exercise (cardiovascular fitness level). However, Barella et al. (2010) did not find a smaller Stroop effect after acute exercise.

This apparent increase in the cognitive impact of exercise in older adults as compared to younger adults (Boucard et al., 2012; Stones & Kozma, 1989) supports the hypothesis that exercise may assist in compensation for age-related cognitive decline. However, greater cognitive impact on older adults than younger adults has not been consistently replicated (Bunce & Murden, 2006). Furthermore, a meta-regression analysis by Etnier et al. (2006) revealed no correlation between cardiovascular activity and cognitive ability, contradicting the claim that age and physical fitness are moderators for exercise effects in this population proposed by Stones and Kozma (1989) and Boucard et al. (2012).

The limited number of studies indicate that further research is needed in order to 1) verify the mechanism(s) behind these changes and 2) determine the effects of acute exercise on the cognition of older adults, as the majority of present studies utilize chronic dosage. Though cognitive effects have been well documented, linguistic effects are less understood. The next section will discuss possible implications for language processing.

Potential Impact of Acute Exercise on Language Processing

Language is a fast-paced cognitive function. Neuroimaging and behavioral measures have been utilized to explore neurological coordinates, connectivity, and timing of language functions, specifically the components of word retrieval and production, which occur in a matter of milliseconds (Indefrey, 2011). Indeed, if exercise improves general cognitive speed, it is thought that exercise would facilitate speeded linguistic processing as well. Furthermore, in terms of aging, age-related changes in language processing, namely in terms of lexical retrieval, may improve as a result of improved processing speed, as general processing speed has been linked to word retrieval speed (Faroqi-Shah & Gehman, under review).

As language is heavily reliant on speeded processing, the previously mentioned *speed hypothesis* has implications for exercise effects on this cognitive function. In a previous study, Faroqi-Shah et al. (in prep) explored the cognitive and linguistic effects of a single bout of acute exercise (25-minutes of cycling with exertion not exceeding 65% max heartrate) compared to a sedentary control condition (25-minute TED talk video). The study evaluated domain-general processing speed, domain-general inhibitory control, and language in terms of speed and inhibition (Table 1) in neurotypical college-aged adults. The Pattern Comparison task measures domain-general processing speed through simple reaction time. The participants decide whether two simultaneously presented images are the same or not. The Stroop task measures domain-general inhibitory control though presentation of a series of congruent and incongruent color-word stimuli. Stroop effect in this study was calculated by subtracting neutral from incongruent trials. The Lexical Decision task, the linguistic analog of processing speed, exercises word recognition through presentation of words and non-words. Participants decide whether stimuli are true English words or nonwords. Phoneme monitoring, the linguistic analog of inhibitory control, evaluates lexical retrieval through presentation of a single phoneme (e.g., /K/) preceding an image. Participants decide whether the target word (presented in the image) contains the presented phoneme.

Table 1.
Younger adult study (Faroqi-Shah et al., in prep) experimental tasks

	Domain-General	Language
Speed	Pattern Comparison	Lexical Decision
Control	Stroop	Phoneme Monitoring

Results indicated that acute exercise improved domain-general processing speed and linguistic processing speed as evidenced by shorter response times on the Pattern Comparison and Lexical Decision tasks, respectively, relative to a control task that included watching a video for 25 minutes. However, Stroop effect did not become smaller after the cycling condition, and reaction times for the Phoneme Monitoring task did not shorten after the cycling condition. This indicates that domain-general and lexical inhibition did not improve as a result of acute exercise.

In order to control for practice effects from repeating the same experimental task, Faroqi-Shah et al., (in prep) developed four matched versions of their experimental tasks (Stroop, Lexical Decision, Processing Speed and Phoneme Monitoring). In spite of this, they reported practice effects in their study across time points. In the two tasks that showed an interaction between time and condition (cycling versus control), and thus greater speed-up in the exercise condition relative to the control condition, exercise induced faster processing over and above the practice effect.

The results of this study support the speed hypothesis (arousal effect) of exercise rather than the inhibition hypothesis. Others have explored this *speed hypothesis* of exercise and cognition using both acute and chronic dosage with similar results (McMorris et al., 2011; Hillman et al., 2006). To our knowledge, Faroqi-Shah et al.'s is the first study to examine the effects of exercise on language in young adults, and there is no study that has examined language effects in older adults.

Language and Aging

In addition to physiological and cognitive changes, aging impacts linguistic processing at the word, sentence, and discourse level. These have implications for communication, as well as psychosocial well-being (Thornton & Light, 2006). It is thought that as people age, a shift in language processing strategies occurs. Increased recruitment of top-down processing, as opposed to bottom-up processing, is seen, possibly to compensate for reduced efficiency in cognitive processing (Thornton & Light, 2006). Though vocabulary grows with age, older adults experience the "tip of the tongue" state more frequently than younger adults do. Two theories have been proposed in an attempt to explain this increase in word retrieval deficits with age. The inhibition deficit hypothesis suggests that older individuals have more difficulty suppressing irrelevant information, and thus retrieving the correct word. The transmission deficit hypothesis suggests that weakened memory connections in the aging brain are responsible (Thornton & Light, 2006). Given that acute exercise has shown to improve connectivity and functionality in terms of blood flow and BDNF concentration in hippocampal memory networks (Voss et al., 2019; Griffin et al., 2011; Thornton & Light, 2006) it is possible that lexical recognition can be improved in older adults after exercise to a greater extent than what Faroqi-Shah et al. measured in younger adults.

Summary

To summarize, two of the possible mechanisms by which acute exercise might impact cognition are that exercise may induce increased arousal, thus speeding cognitive processes, and exercise may increase connectivity of inhibitory networks, improving inhibitory control (Lambourne & Tomporowski, 2010; Tomporowski & Ellis, 1986). The evidence reviewed so far suggests greater support for processing speed (Chang et al., 2014; Rattray & Shmee, 2013; Barella et al., 2010; Davranche et al., 2006) than for inhibitory control (Alves et al., 2012; Boucard et al, 2012; O'Leary et al., 2011; Sibley, Etnier, & Le Masurier, 2006). Several studies have not found improved inhibitory control with exercise (Chang et al. 2014; Barella et al. 2010; Smiley-Oyen, et al., 2008; Etnier et al., 2006). However, it is likely that exercise may have larger effects on inhibitory control in older adults (Boucard et al., 2012; Stones & Kozma, 1989), as a compensation for age-related cognitive decline. Additionally, because linguistic changes occur as part of the normal aging process, the impact of acute exercise may be greater for this population as compared to their younger adult counterparts. Empirical support exists for both of the reviewed exercise hypotheses (speed and inhibition) in older adults, indicating that more research is needed in order to understand the underlying mechanisms in this population, and potentially harness these during rehabilitation, to compensate for age-related cognitive (and linguistic) decline. Therefore, a follow-up study to Faroqi-Shah et al.'s (in prep) original study is needed in order to better understand the effects of acute exercise on the cognitive and linguistic performance of older adults and explore whether these appear to be facilitated by improving speed, improving inhibition, or both.

Chapter 3: Research Questions and Hypotheses

This study aims to examine the effects of acute exercise on language and cognitive processing in older adults. Additionally, if exercise effects are seen in this population, we aim to determine if changes in language and cognition can be attributed to changes in speed or inhibitory control. The following research questions and hypotheses are posed:

Question 1

Does acute exercise impact general processing speed in healthy older adults (as it did in younger adults)? Based on prior research showing increased processing speed for both younger (Rattray & Shmee, 2013; Davranche et al., 2006; Faroqi-Shah et al., in prep), and older (Chang et al., 2014; Barella et al., 2010) adults, it is hypothesized that older adults will show improved processing speed in domain general processing speed in the exercise condition relative to a control condition. Alternatively, it is possible that age-related cognitive slowing could induce smaller or no effect on processing speed in this population, therefore not improving cognitive processing in terms of speeded simple reaction time as a result of the acute exercise protocol. This alternative hypothesis is supported by findings in the literature indicating smaller behavioral effects of exercise in older adults as compared to younger adults (see Bunce & Murden, 2006), which suggest that age-related cognitive slowing could induce smaller or no effect on processing speed in this population.

Question 2

Does acute exercise impact general inhibitory control in healthy older adults? Based on prior research showing improved inhibitory control in older adults as a result of exercise (Won et al., 2019b; Boucard et al., 2012), it is hypothesized that this population will show improved inhibitory control in both domain general inhibition in the exercise condition. Alternatively, given that younger adults did not show any change in the Stroop effect as a result of acute exercise (Faroqi-Shah et al.), it is possible that inhibitory effects will not be seen in older adults as a result of exercise.

Question 3

Does acute exercise impact lexical processing, as measured by lexical speed (lexical decision task) and lexical inhibition (picture verification task) in healthy older adults? These tasks are analogous to the domain general speed (processing speed task) and domain general inhibitory control (Stroop task) tasks, respectively. It is hypothesized that older adults will show improved lexical processing in terms of lexical speed (lexical decision), just as younger adults did (Faroqi-Shah et al., in prep). Significant improvements in word retrieval, specifically in lexical inhibition (Picture Verification task) not previously found in younger adults may be seen in this population, as linguistic processing is a cognitive function that relies on speed (Indefrey, 2011), and a correlation has been found between processing speed and word retrieval speed (Faroqi-Shah & Gehman, under review). Additionally, inhibitory control declines during the healthy aging process (Dempster, 1992) and it is possible that exercise effects may not be significant enough to overcome these age-related changes.

Question 4

Are the effects of acute exercise larger in older adults as compared to younger adults? This question will be addressed using the young adult data from Faroqi-Shah et al (in prep) and comparing with the older adult data from the current study. It is hypothesized that performance on all tasks will be significantly greater in older adults than younger adults in the exercise condition (compared to their respective baselines), as general cognitive slowing, word retrieval, and lexical decision are all impacted during the normal aging process (Thornton & Light, 2006). Furthermore, research has shown that inhibition and task switching ability have improved in older adults compared to younger adults as a result of exercise (Boucard et al., 2012; Stones & Kozma, 1989).

Chapter 4: Methods

Overall Study Design

This study used a within-group repeated measures design. The effects of acute exercise were compared with a control task (watching a TED talk) in order to rule out possible practice effects from administering the experimental tasks twice on the same day. Four different versions of each experimental task were utilized pre and post for both the exercise and control conditions in an effort to minimize practice effect. Participants were administered computerized experimental tasks immediately before and after the exercise and control tasks. The independent variables were condition (exercise, video), and time (pre-exercise, post-exercise), and the primary dependent variable across all tasks were reaction time, as well as Stroop effect for the Stroop task. To answer the first research question, a computerized Pattern Comparison task was used to evaluate the effect of acute exercise on general processing speed. To answer the second research question, the Stroop task was utilized in order to determine the effect of exercise on inhibitory control. For the third research question, two tasks, a Lexical Decision task to measure word recognition abilities, and a Picture Verification task to measure word retrieval abilities, were utilized to evaluate the effects of acute exercise on lexical performance. The Picture Verification task evaluates lexical inhibition in terms of lexical retrieval, as participants must view an image, retrieve a word based on a target image, and make a decision regarding whether the word matches the preceding target image. The word either matched the target image or was semantically related to the target image (but not an exact match), thus recruiting inhibitory control.

Participants

Participants were recruited from the local community and included twenty-one healthy adults (eight males and thirteen females) between the ages of 58 and 75 (M=66, SD=4.7). Mean education level was 18 years (range=12-25 years, SD=3.6). A 6-item screening questionnaire called the Exercise Assessment and Screening for You (EASY) questionnaire, which asks participants a series of six questions relating to their current health status, was administered to ensure the exercise regimen could be safely completed by all participants (Resnick et al., 2008a). This questionnaire was made specifically for older adults and screens for cardiovascular risk factors that may impact the individual's ability to exercise safely. Participants responded negatively to a minimum of five of six questions to be eligible to participate in the study (Resnick et al., 2008b). An additional general health history form was administered to screen for any serious medical issues that may pose a safety risk. The physical activity portion of the CHAMPS Activities Questionnaire for Older Adults (Stewart, Mills, King, Haskell, Gillis & Ritter, 2001), which evaluates frequency and type of regular physical activity, was administered in order to evaluate general exercise behavior. Weekly exercise ranged from about 3 to about 32 hours, with the average amount of weekly exercise in the sample being 12 hours a week (SD=7.8). Over 60% of participants (13/21) exercised 10 or more hours per week.

Additional inclusionary criteria were as follows: normal cognition, no history of speech-language diagnoses, neuropsychiatric conditions, substance abuse, normal or corrected-to-normal vision and color perception (for the Stroop task), and the ability to get on and off a stationary exercise bicycle with minimal assistance. Normal cognition was determined by a score equal to or above 26/30 on the Montreal Cognitive Assessment (M=28.8, SD=1.2, range=26-30) (Nasreddine et al., 2005).

Statistical Power

Previously obtained data from young adults was used to determine the minimum number of participants needed in this study to meet a statistical power of .80 at $p<.05$. G-power 3.1.9.6. software was used to compute the sample size. Results indicated that at least seven participants were needed based on the effect size seen in the young adult group.

Procedures

Participants who passed the EASY screening questionnaire (on the phone) were scheduled for the study. After providing informed consent and completing screening tasks detailed above, experimental tasks were administered. Each participant completed (different versions) of the four experimental tasks before and after the exercise and control conditions on two separate days. Conditions were presented approximately seven days apart. The order of testing was counterbalanced among participants for both sequence of control/experimental condition and the four experimental tasks. Participants were paid for taking part in the study.

Experimental Tasks and Stimuli

Control Condition: The control condition was comprised of watching a TED Talk Video titled “My Wish: Once Upon a School” matching exercise duration (25 min) (Eggers, 2008). Note that participants were not allowed to listen to music, etc. during either the control or exercise conditions.

Experimental Condition (Acute Exercise Condition): Five minutes of warm-up, twenty-five minutes of moderate intensity cycling, and ten minutes of rest were closely monitored by the researcher. Heartrate was recorded on three-minute intervals in order to ensure heart rate did not exceed 65% maximal capacity as measured by a Beeasy fitness tracker (heartrate watch) worn on the participant’s wrist. Sixty-five percent perceived maximal heartrate was based on age.

Exertion was monitored using the Borg Rating of Perceived Exertion (RPE) (Borg, 1982) to determine subjective exertion levels every three minutes. The scale ranges from 6 to 20 (no exertion and maximum exertion, respectively). Participants were instructed to remain around a level 13 (moderate intensity). The scale was displayed in front of the participants while they were cycling. They were encouraged to raise resistance or pedal faster if their RPE fell below 13.

Experimental tasks utilized in the original study (Faroqi-Shah et al., in prep) were utilized in this study, aside from the Picture Verification task, which was created for this experiment and replaced the Phoneme Monitoring task used in the young adult study. Experimental tasks were created using PsychoPy software version 2.3 (Pierce, 2007). Given that each participant was administered each experimental task four times (before and after exercise and control), each of the experimental tasks below had four equivalent versions. The four versions of each task are matched for accuracy and RT, based on performance in a group of 20 young adults.

Pattern Comparison: A Pattern Comparison task modeled after National Institutes of Health (NIH) Toolbox (nihtoolbox.org, Carlozzi, Tulsky, Kail, & Beaumont, 2014) was utilized to evaluate domain general processing speed. The task took approximately five minutes and involved making a same-different judgment in response to two pictures presented simultaneously side-by-side on a computer screen by pressing one of two keys on a keyboard. There were 10 practice trials, followed by 90 experimental trials (half same, half different) presented in a random sequence.

Stroop: This task involves seeing a word on the screen and identifying the font color by pressing one of three arrow keys, as there will be three different stimulus conditions. In the congruent condition, the font color matched the meaning of the word (e.g., the word “purple” will be displayed in purple ink). In the incongruent condition, the font color did not match the word meaning. In the neutral condition, the word “plan” was written in one of the three font color options described to the participant. There were 6 practice trials followed by 180 experimental trials (60 neutral, 60 congruent, 60 incongruent).

Lexical Decision: For this task, participants saw a series of letters on the screen and determined if it is a true word in English or not by pressing one of two keys on the keyboard. A ‘+’ symbol flashed on the screen before each stimulus item in order to focus participants to the center of the screen. Four practice trials, followed by 136 experimental trials (half words, half nonwords) were administered.

Picture Verification: This task involved displaying a picture depicting an action or an object on the screen, followed by a single word. Target images were retrieved from the International Picture Naming Project online master database (http://crl.ucsd.edu/~aszekely/ipnp/); images with an 80% agreement rating or higher were chosen in order to reduce ambiguity surrounding the action/object the picture is intended to depict. Participants were instructed to press a key to indicate whether or not the presented word matched the word that the picture depicted (Szekely et al., 2005). Before each stimulus item, a '+' symbol flashed on the screen to focus participants to the center of the screen. Presented words either matched the target image or were semantically related to the target image. Semantically related words were chosen utilizing the Wordnet Lexical Database (Princeton University, 2010). One of the first three semantically related words under the target word definition was utilized. There were 9 practice trials and 69 experimental trials (half action, half objects).

Data Analysis

Statistical Package for Social Sciences (SPSS) version 2.4 was used for statistical analyses. Statistical significance was determined utilizing an alpha value of 0.05. The primary outcome measure for all four experimental tasks was reaction time (ms) for correctly answered trials. Data cleaning for evaluation of the effect of condition on speed (RT) involved removal of incorrect trials. For the first three research questions, RTs were analyzed using linear mixed effect analyses with condition and time as fixed effects and participant and trial as random effects. Intercept and random slope were included in the model. Proportion accuracy was calculated for each experimental task; data from participants whose proportion accuracy fell below .75 on any given task were removed from the statistical analysis for that task. Two-way univariate Analysis of Variance (ANOVA) (condition x time) was used for accuracy analysis, For the fourth research question, which compared young and older adults, RTs of the cycling condition were compared using linear mixed effects model with age group and time as the fixed effects, participants as random effects, intercept and random slopes included in the model. Accuracies were compared using a 2-way ANOVA (age x time).

Chapter 5: Results

Fitness Level, Heart Rate, and Exertion

Average heartrate was 97.7 BPM (SD = 11.4, range: 72-134 BPM). Average RPE (Borg, 1982) was 13.2 (SD=0.44, range: 11-15). For the first three minutes, the average HR was 92.6 BPM (SD=15.3, range=72-124), and average RPE was 12.1 (SD=1.0, range=10-14). For the middle ten minutes, the average HR was 102.4 (SD=13.1, range=80-127), and average RPE was 13.3 (SD=0.6, range=13-15). For the last three minutes, the average HR was 100.7 (SD=15.1, range=77-127), and average RPE was 13.2 (SD=0.6, range=12-14).

Mean accuracies for each task in both conditions for older adults are located in Table 2. Mean reaction times for all four experimental tasks are presented in Table 4 and illustrated in Figures 1-4.

Table 2.

Proportion accuracy for all four computer tasks and results of statistical analyses

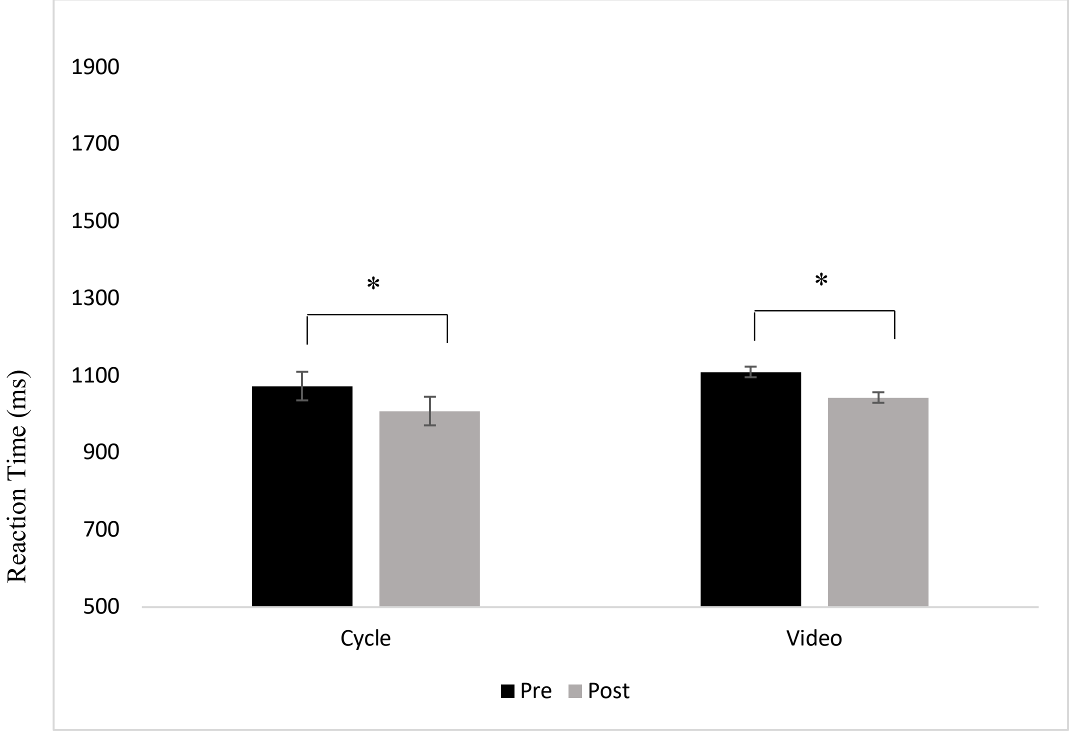
Task	**Cycling** ***(M, SD)***		**Video** ***(M, SD)***		**p-value (*condition, time, condition*time*)**
Pattern Comparison	Pre	0.865, 0.040	Pre	0.878, 0.034	0.811, 0.091, 0.368
	Post	0. 888, 0.042	Post	0.885, 0.040	
Stroop					
Congruent	Pre	0.991, 0.018	Pre	0.996, 0.007	- -
	Post	0.990, 0.012	Post	0.989, 0.017	
Incongruent	Pre	0.975, 0.031	Pre	0.975, 0.028	- -
	Post	0.976, 0.024	Post	0. 979, 0.017	
Neutral	Pre	0.995, 0.011	Pre	0.995, 0.010	- -
	Post	0.986, 0.023	Post	0.985, 0.011	
Stroop Effect	Pre	-0.020, 0.029	Pre	-0.020, 0.028	0.938, 0.055, 0.938
	Post	-0.010, 0.016	Post.	-0.010, 0.017	
Lexical Decision	Pre	0.980, 0.033	Pre	0.937, 0.042	0.260, 0.288, 0.356
	Post	0.986, 0.014	Post	0.940, 0.030	
Picture Verification	Pre	0.903, 0.067	Pre	0.903, 0.064	0.393, 0.333, 0.393
	Post	0.895, 0.065	Post	0.903, 0.076	

Table 3.
Older adult mean reaction times for all four computer tasks – Reported in milliseconds

Task	**Cycling (M, SD)**	**Video (M, SD)**	**p-value (condition, time, condition* time)**
Pattern Comparison	Pre 1098.750, 576.084	Pre 1113.756, 646.968	0.001* 0.000*, 0.957
	Post 1031.150, 411.002	Post 1040.422, 475.073	
Stroop			
Congruent	Pre 929.112, 405.974	Pre 960.173, 561.853	
	Post 851.495, 360.527	Post 883.125, 427.545	
Incongruent	Pre 1133.626, 468.446	Pre 1162.310, 812.717	
	Post 999.326, 403.713	Post 1041.130, 487.757	
Neutral	Pre 959.287, 393.403	Pre 989.061, 587.500	
	Post 888.796, 379.090	Post 926.082, 480.835	
Stroop Effect	Pre 172.116, 127.509	Pre 176.953, 186.351	0.856, 0.014*, 0.988
	Post 110.768, 73.545	Post. 114.862, 101.392	
Lexical Decision	Pre 1592.267, 445.642	Pre 1627.485, 446.276	0.000*,0.000*,0.101
	Post 1506.110, 336.253	Post 1564.125, 419.383	
Picture Verification	Pre 1102.060, 446.267	Pre 1088.519, 467.042	0.261, 0.000*, 0.218
	Post 956.140, 415.004	Post 1003.879, 442.96	

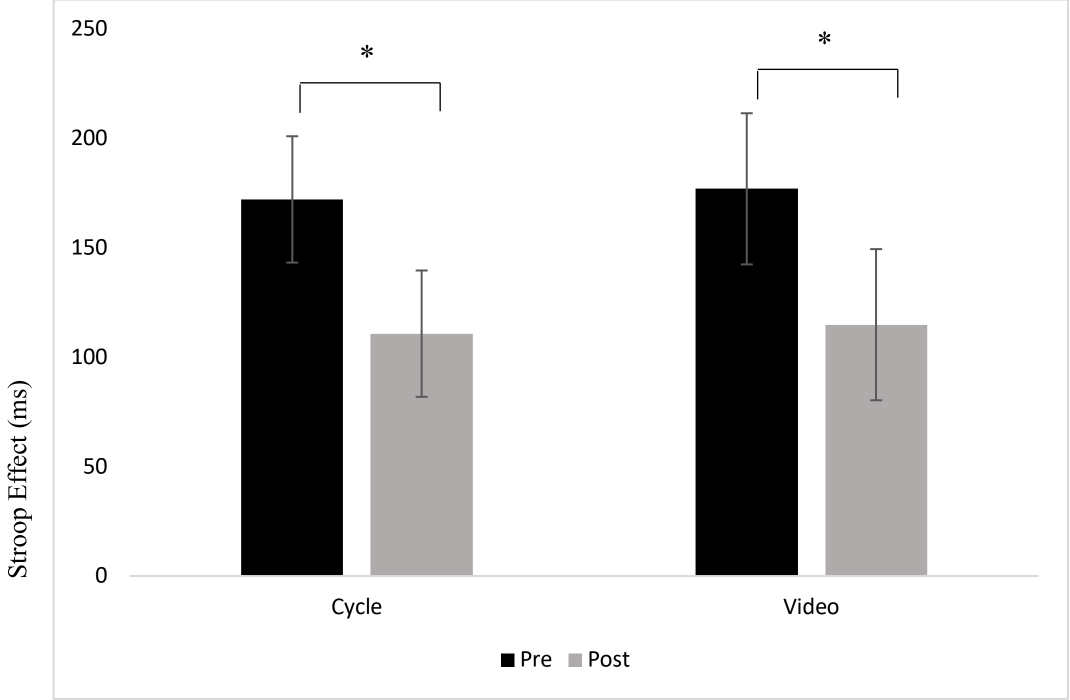
*=statistically significant, $p<0.05$

Figure 1. *Processing speed as a function of experimental condition and time*



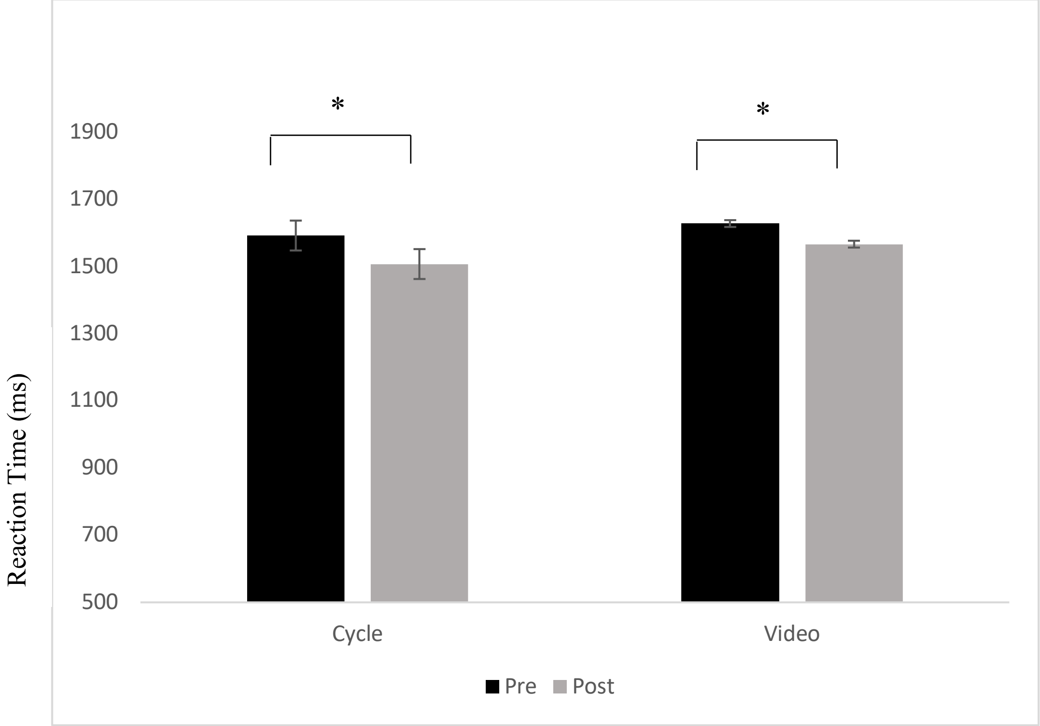
*= statistically significant, p<0.05

Figure 2. *Stroop effect as a function of experimental condition and time*



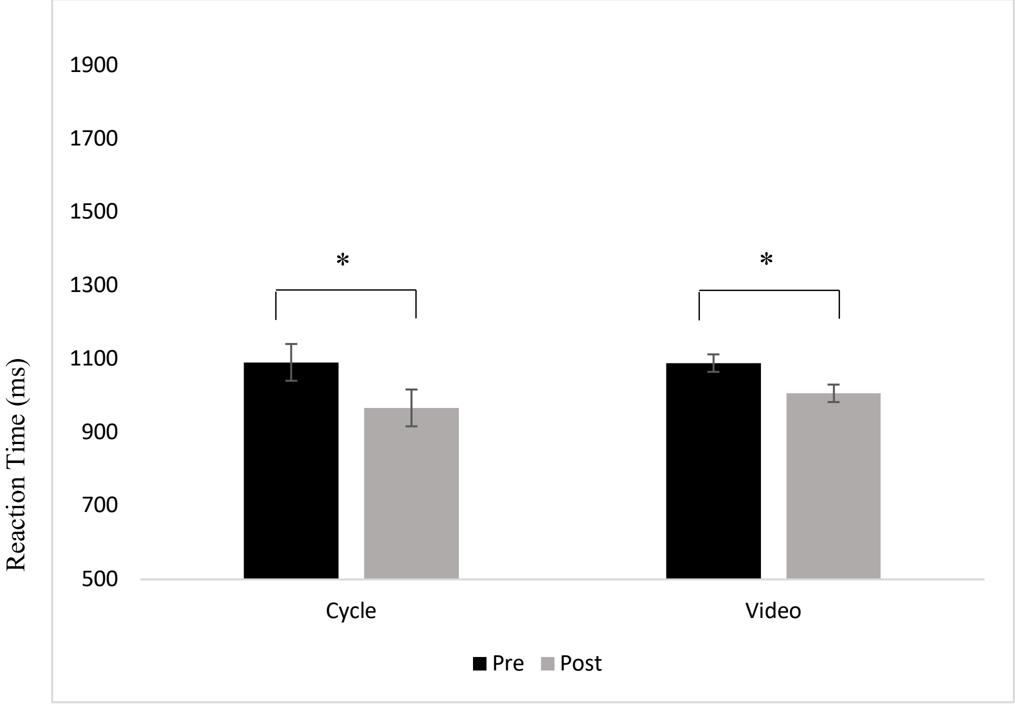
*= statistically significant, p<0.05

Figure 3. *Lexical decision as a function of experimental condition and time*



*= statistically significant, p<0.05

Figure 4. *Picture verification as a function of experimental condition and time*



*= statistically significant, p<0.05

Question 1: Effect of Acute Exercise on Processing Speed

Changes in accuracy were not statistically significant across time (pre, post) and condition (video, cycle) (Table 2).

For reaction time (measured during the Pattern Comparison task) significant differences for condition (β=-35.101, SE= 13.700, p=0.001) and time (β=66.325, SE= 13.125, p=0.000) were seen, with no significant interaction between condition and time (β=-1.552, SE=19.149, p=0.957). The main effect of condition showed significantly slower reaction times in the video condition compared to the cycling condition. The main effect of time with shorter RTs in the post-session and no interaction between condition and time shows that RTs were faster in the post-testing compared to pre-testing for both video and cycling. This indicates a with-in session practice effect (Table 3).

Question 2: Effect of Acute Exercise on Inhibitory Control

Inhibitory control was measured as the Stroop effect, which is the difference in performance between the incongruent and neutral conditions. There were no significant effects of time or condition in Stroop effect accuracies (Table 2). Similarly, for speed, there were no significant differences in condition (β=-4.094, SE= 10.186, p=0.856) or the interaction between condition and time (β=-0.742, SE= 14.402, p=0.988). There was a significant effect of time (β=62.091, SE= 10.305, p=0.014), with smaller Stroop Effect in the post-session, indicating a practice effect for both conditions (Table 3).

Question 3: Effect of Acute Exercise on Lexical Processing

Speed and accuracy data from the Lexical Decision and Picture Verification tasks were used to answer the third research question. Table 2 shows that there were no significant effects of time, condition or interaction between time and condition for accuracy on the lexical decision and picture verification tasks.

For reaction time on the Lexical Decision task, significant differences for condition (β=-59.281, SE=34.542, p=0.000) and time (β=61.256, SE=34.524, p=0.000), with no significant interaction between condition and time (β=23.636, SE=48.850, p=0.101). The main effect for condition indicates significantly slower RTs in the video condition compared to the cycling condition. The main effect of time with no interaction between condition and time indicates shorter RTs in the post session and a within-session practice effect for both conditions.

For reaction time on the Picture Verification task, there were nonsignificant differences for condition (β=-39.684, SE =23.817 , p=0.261), significant differences for time (β=82.345, SE=23.675, p=0.000), and no significant interaction between condition and time (β=41.534, SE=33.674, p=0.218). Main effect of time with no interaction between condition and time indicates shorter RTs for the post session and a within-session practice effect for both conditions (Table 3).

Proportion accuracies of the young and older groups together are listed in Table 3. As a new lexical inhibition task was created for the older adult study (Picture Verification), only the three computer tasks completed by both the young and old adult groups (Pattern Comparison, Stroop, Lexical Decision) are compared in Table

3. Statistical analyses of reaction times of younger and older adult groups for the three shared computer tasks are in located Table 5.

Table 4.

Results of the statistical analyses comparing proportion accuracy of young and old groups for three shared computer tasks

		Cycling		**Video**	
Task	**Group**	***(M, SD)***	**p-value (group, time, group*time)**	***(M, SD)***	**p-value (video group, time, group* time)**
Pattern Comparison	Young	Pre .875, 0.053	0.271, 0.141, 0.198	Pre .885, 0.045	0.190, 0.650, 0.195
		Post .873, 0.046		Post .868, 0.063	
	Old	Pre .865, 0.040		Pre .878, 0.034	
		Post .888, 0.042		Post .885, 0.040	
Stroop Effect	Young	Pre -.028, 0.059	0.561, 0.431, 0.906	Pre -.026, 0.051	0.409, 0.494, 0.804
		Post -.016,0.037		Post -.020,0.054	
	Old	Pre -.020, 0.029		Pre -.020, 0.028	
		Post -.010,0.016		Post -.010,0.017	
Lexical Decision*	Young	Pre .893, 0.051	0.000*, 0.873, 0.454	Pre .899, 0.055	0.000*, 0.847, 0.101
		Post .864, 0.075		Post .869, 0.063	
	Old	Pre .980, 0.033		Pre .937, 0.042	
		Post .986, 0.014		Post .940, 0.030	

*=statistically significant, $p<0.05$

Table 5.

Results of the statistical analyses comparing reaction times of young and old groups for three shared computer tasks in the cycling condition

Task	**Group**	***(M, SD)***		**p-value (*group, time, group*time*)**
Pattern Comparison	Young	Pre	769.429, 284.794	0.000*, 0.000*, 0.443
		Post	687.619, 192.251	
	Old	Pre	1098.750, 576.084	
		Post	1031.150, 411.002	
Stroop Effect	Young	Pre	52.916, 29.235	0.001*, 0.006*, 0.024*
		Post	49.202, 33.615	
	Old	Pre	172.116, 127.509	
		Post	110.768, 73.545	
Lexical Decision	Young	Pre	1281.809, 288.362	0.000*, 0.000*, 0.162
		Post	1326.081, 370.982	
	Old	Pre	1592.267, 445.642	
		Post	1506.110, 336.253	

*=statistically significant, $p<0.05$

Question 4: Age Differences on the Effects of Exercise

Significant interaction for group was seen for accuracy in the cycling (β=-.122, SE=.032, p=0.000) condition for the Lexical Decision task, indicating that performance accuracy was significantly higher in older adults than younger adults for this task. No other interactions were significant (Table 4, Table 5). Though not part of the original research question, video data from the young and old adult groups was compared. Results from linear mixed effects analyses with time and group (age) as fixed effects, and participant and trial as random effects. The results are located in Appendix A.

For reaction time in the Pattern Comparison task, there was no significant interaction between group and time (β =10.080, SE=13.139, p=0.443), though there were significant differences for group (β=-337.005, SE= 32.799, p=0.000) and time (β=73.906, SE= 9.903, p=0.000). The main effect of group indicates shorter RTs in the young adult group compared to the old adult group in the pre and post sessions. Shorter RTs in the post session with no interaction between group and time indicate a within-session practice effect for both groups.

For reaction time in the Lexical Decision task, no significant interaction between group and time (β =-14.781, SE=10.576, p=0.162) was seen, with significant differences for group (β=-300.637, SE= 40.695, p=0.000) and time (β =86.492, SE= 8.266, p=0.000). The main effect of group indicates shorter RTs for the young adult group compared to the old adult group in pre and post sessions. Main effect of time with no interaction between condition and time indicates a within-session practice effect for both groups.

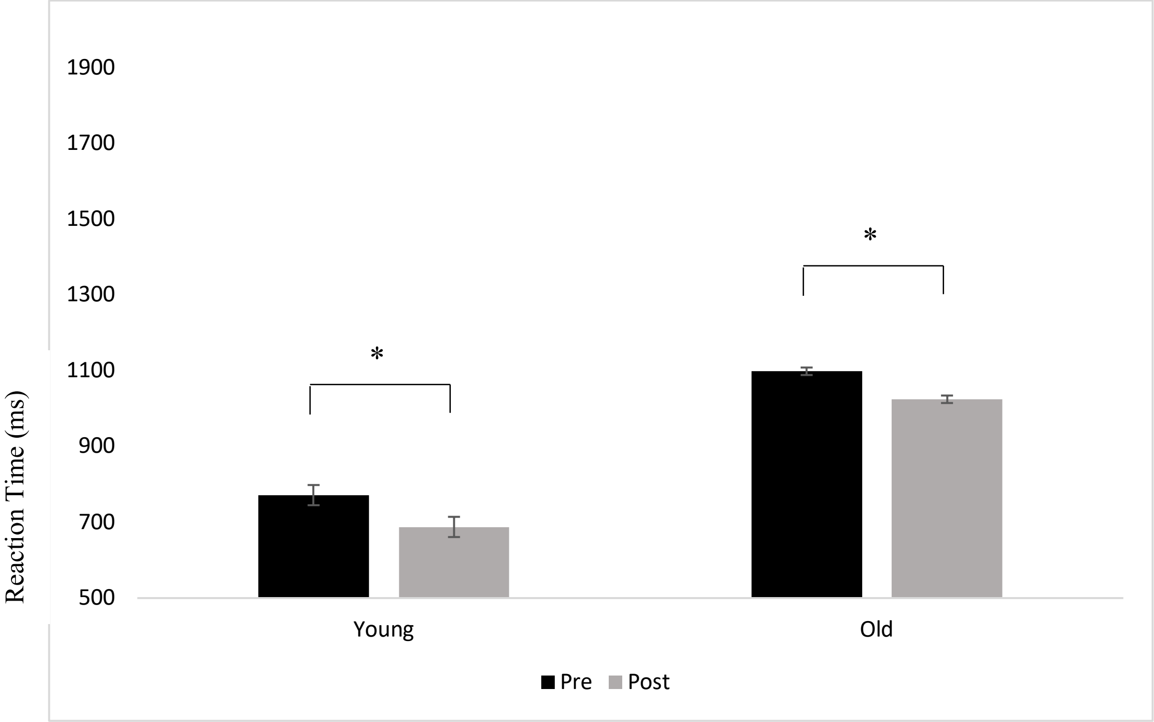
For the Stroop Task, a significant interaction between group and time (β=59.898, SE=26.245, p=0.024), with significant differences for group (β =-61.998, SE=22.134, p=0.006), and time (β=61.720, SE=18.783, p=0.001) were seen. Main effect of time indicates a within-session practice effect for both groups. A main effect of group with shorter RTs in the young adult group indicates significantly slower reaction time for older adults compared to younger adults. An interaction between group and time indicates that older adults had significantly smaller Stroop effect (smaller reaction time differences between incongruent and neutral trials) after the cycling condition compared to their younger counterparts. This likely indicates a stronger practice effect in older adults in the acute exercise condition when compared to younger adults, as Stroop task performance did not significantly improve in the older adult group as a result of exercise relative to video (Table 4).

When comparing younger and older adult accuracy data for the Pattern Comparison task, no interaction between group and time (β=.025, SE=.019, p=0.198) was seen, with nonsignificant interactions for group (β=-.122, SE=.032, p=0.271) and time (β=-.023, SE=.016, p=0.141) for the cycling condition. For the video condition, no interaction between group and time (β=.025, SE=.019, p=0.195) was seen, with nonsignificant interactions for group (β=-.018, SE=.013, p=0.190) and time (β=-.007, SE=.015, p=0.650) (Table 3). This indicates no differences between groups on performance accuracy.

When comparing younger and older adult Stroop task accuracy data, no interaction between group and time (β=.-002, SE= .016, p=0.906) with nonsignificant interactions for group (β=-.007, SE= .011, p=0.561) and time (β=-.010, SE=.013, p=0.431) were seen in the cycling condition. For the video condition, no interaction between group and time (β=.004 SE=.017, p=0.804) was seen, with nonsignificant interactions for group (β=-.010, SE=.012, p=0.409) and time (β=-.010, SE=.014, p=0.494). This indicates no effect of group on performance accuracy.

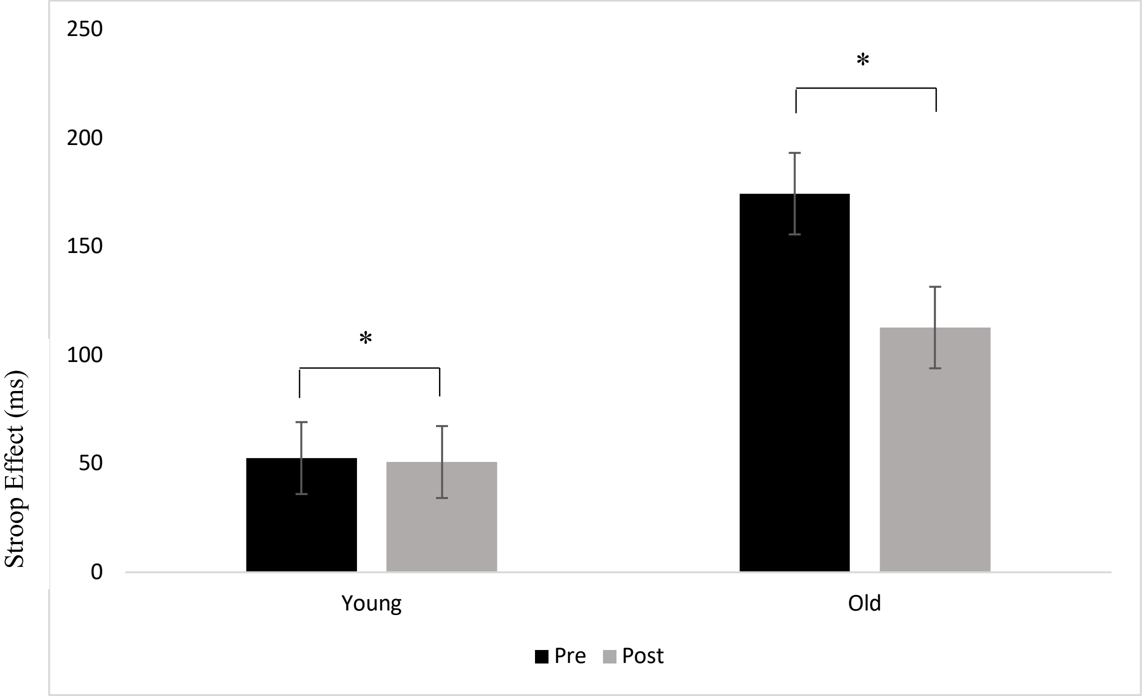
For the Lexical Decision task, comparison of accuracy data between older and younger adult groups revealed no interaction between group and time (β=.035, SE=.046, p=0.454), with a significant interaction for group (β=-.122, SE=.032, p=0.000) and nonsignificant interaction for time (β=-.006, SE=.037, p=0.873) in the cycling condition. In the video condition, no interaction between group and time (β=.033, SE= .020, p=0.101) was seen, with a significant interaction for group (β=-.071, SE=.014, p=0.000), and a nonsignificant interaction for time (β=-.003, SE=.016, p=0.847. The main effect of group indicates that older adults performed significantly more accurately than younger adults on this task for both conditions (Table 3). Interactions are presented in Figures 5-7 with condition as the Y axis and reaction time (ms) as the X axis.

Figure 5. *Processing speed as a function of group and time*



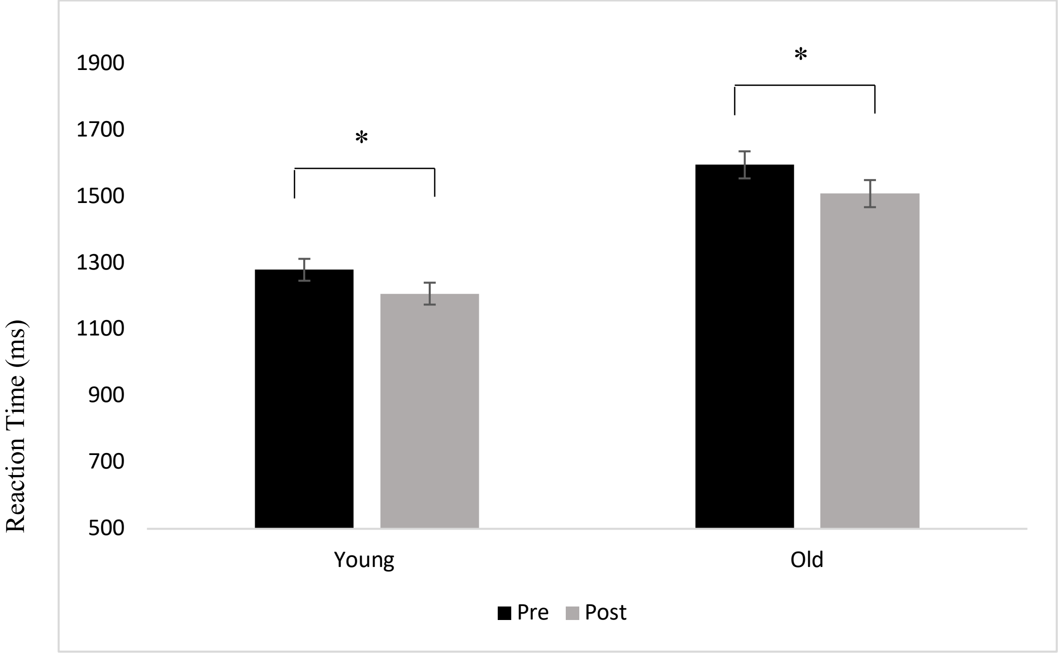
*= statistically significant, p<0.05

Figure 6. *Stroop effect as a function of group and time* *



*= statistically significant, p<0.05

Figure 7. *Lexical decision as a function of group and time*



*= statistically significant, $p<0.05$

Chapter 6: Discussion

The goal of this study was to investigate the cognitive and linguistic effects of exercise on older adults (55+ years) and, if effects were present, to determine the possible mechanism(s) of these effects in terms of speed and inhibition. Additionally, this study aimed to compare current older adult findings to previous findings in younger adults (18-25 years). It was hypothesized that improvements in cognitive and lexical speed (evidenced by shorter reaction times) seen in younger adults as a result of exercise would be significantly larger in older adults for both cognitive and linguistic tasks. This study found that reaction time did not improve significantly in older adults as a result of acute cycling for cognitive or linguistic tasks. In comparison of young and old adult cycling data, there were no significant interactions (i.e. greater exercise effect in older adults) for Processing Speed and Lexical Decision. But there was a significant interaction between group and time for the Stroop task. Specifically, the Stroop effect in older adults became significantly smaller after cycling when compared to young adults. However, as there was no main effect of exercise relative to video for the Stroop task in the older adult group alone, this finding likely indicates a greater practice effect for older adults than younger adults for this task rather than a true exercise effect.

In older adults, accuracy scores did not significantly improve as a function of time or condition, though accuracy scores were notably high pre and post for both conditions (averages between 87% and 99%). Interestingly, task accuracies of younger adults were lower than older adults for the lexical decision task. The implications of these findings are discussed in the following sections.

Exertion in the Cycling Condition

Before discussing the findings of the experimental tasks, it is important to consider if the older adults in this study reached a moderate intensity of physical exertion in the cycling condition as intensity level has shown to influence the cognitive impact of exercise in the acute dosage. Specifically, moderate intensity exercise has had positive cognitive effects (Davaranche, et al., 2006; Faroqi-Shah et al., in prep). Conversely, low intensity self-paced exercise and maximal intensity exercise have had negative cognitive effects (Pontifex & Hillman, 2007; McMorris & Keen, 1994). The aim of this study was for participants to exercise at moderate intensity, as measured by perceived a Borg Perceived Exertion of around 13 ("Somewhat Hard" exercise). Heart rate was also measured to monitor any apparent overexertion as, based on previous findings, overexertion or under-exertion during acute exercise would likely dampen cognitive effects.

RPE scores were consistent among participants but heart rate was not, indicating a possible range of exertion within and between subjects evidenced by differences in physiological measures. That is, despite consistent report of moderate exertion by participants (via RPE) during the exercise condition, variance in average heartrate among individual participants (SD = 11.4, range: 72-134 BPM) indicated that exertion may have varied among participants. However, thorough examination of heartrate (M=92.6, SD=15.3) and RPE (M=12.1, SD=1.0) after the first three minutes of exercise, the middle ten minutes of exercise (HR: M=102.4, SD=13.1; RPE: M=13.3, SD=0.6), and the final three minutes of exercise (HR: M=100.7, SD=15.1; RPE: M=13.2, SD=0.6) indicates participant exertion remained relatively stable.

The Centers for Disease Control (2019) suggests that in most individuals, 64% -79% maximum heartrate indicates moderate intensity of exercise. Maximum heartrate is calculated by subtracting participant age from 220 BPM. The average age of this group was 66 (SD=5.2), indicating an average maximum heart rate of approximately 154 BPM, and a moderate intensity heart rate range of 99 BPM to 115 BPM (CDC, 2019). The average heart rate of this group was 97.7 BPM, indicating that many participants may have exerted within the low intensity range rather than the moderate intensity range. However, HR is not always a reliable measure of exertion as it can be influenced by external factors such as environmental temperature (Chen, Fan, & Moe, 2010). Therefore, as RPE scores, a generally accurate measure of exertion (Skaturd-Mickelson, Benson, Hannon & Askew, 2011), indicate that participants were exerting at a moderate intensity, it is likely participants may have indeed achieved good exertion.

In this study, participants exercised for twenty-five minutes. Twenty-five minutes was chosen as the young adult group showed exercise effects on cognitive and lexical speed with twenty-five minutes of exercise, and most acute exercise studies utilize between ten and thirty minutes of exercise. Additionally, a meta-analysis by Lambourne & Tomporowski (2010) revealed negative cognitive effects measured within the first twenty minutes of exercise and positive effects after the first twenty minutes of exercise. Additionally, older adults, unlike younger adults (of Faroqi-Shah et al, in prep), were given a ten-minute rest period after cycling. It is possible that exercise effects seen in younger adults may have dissipated in older adults during this rest period and thus no significant effects were seen. However, Chang et al. (2012) report cognitive effects lasting up to two hours after acute exercise.

Differences in methodology could contribute to differences in study outcomes. One such difference is length of exercise. Previous studies utilized shorter periods of acute exercise than our twenty-five minutes of moderate intensity cycling and found improved speed with ten (Rattray & Shmee, 2013) and fifteen (Davaranche et al., 2006) minutes of moderate intensity cycling. Timing of task administration is another difference that could impact variety in study outcomes. We administered experimental tasks in the exercise condition after a ten-minute rest period whereas Davaranche et al. (2006), who found improved processing speed as a result of acute cycling, measured cognitive performance during exercise. Differences in experimental tasks among studies, which will be discussed specific to each research question, is another factor to consider.

Effect of Acute Exercise on Processing Speed

We hypothesized that older adults would show improved processing speed (shorter RTs) as a result of the exercise condition compared to the control condition as per the arousal hypothesis (Tomporowski & Ellis, 1986) and previous research in younger (Faroqi-Shah et al., in prep; Rattray & Schmee, 2013) and older (Chang et al., 2014; Barella et al., 2010) adults. Our alternative hypothesis was that exercise effects would not be able to overcome age-related cognitive slowing (Salthouse, 1996), and that no improvements in processing speed would be seen.

Previous studies reviewing the effects of exercise on cognitive speed in older adults have had mixed results. Results of the current study are supported by previous findings reporting no improvement in cognitive speed in adults as a result of acute exercise. More evidence exists for the younger adult population (Ando et al., 2005; McMorris & Keen, 1994) than for the older adult population (Pesce & Audiffren, 2003). All studies used a sedentary control condition. Ando et al. (2005) reported a negative effect on reaction time as measured by longer reaction times on a peripheral visual task during maximal intensity acute cycling. McMorris and Keen (1994) found no improvement in simple reaction time during moderate intensity acute cycling, and slowed reaction time during maximal intensity acute cycling, using a simple motor task. Pesce and Audiffren, (2003) evaluated cognitive effects of acute cycling in older adults (65-74) and found no improvement in reaction time during completion of a "low demanding" task switching task. The task was considered "low" in cognitive demand because 80% of trials were congruent in nature.

Studies reporting improved processing speed in older adults as a result of acute exercise (Chang et al., 2014; Barella et al., 2010) do not support the findings of this study. Both Chang et al. (2014) and Barella et al. (2010) utilized a sedentary control condition like the current study. Barella et al. (2010) used the Stroop color test, which included exclusively congruent trials and required participants to orally report a color presented on a screen, to measure information processing speed. Similarly, Chang et al. (2014) derived reaction times from congruent Stroop task items. In order to measure true processing speed, a task of simple reaction time, rather than a complex task such as Stroop or task switch, must be used. Therefore, a parallel comparison cannot be made among findings from the studies in this review and findings from the current study, as pure simple reaction time was not measured in other older adult studies.

Meta-analyses of processing speed in young adults show that, overall, positive effects of acute exercise on cognitive speed are small (Chang et al., 2012; Lambourne & Tomporowski, 2010; Etnier et al., 1997). Table 5 shows that older adults were much slower than younger adults in their overall RT. This is consistent with the well-established slowing with age (Salthouse, 1996; Goh & Park, 2012). Thus, cognitive effects of acute exercise, which are reported to be small in effect size (Chang et al., 2012; Lambourne & Tomporowski, 2010; Etnier et al., 1997) may not be great enough to overcome age-related cognitive slowing. This implies that the arousal hypothesis of acute exercise reported in the younger adult population is not significantly or consistently replicated in the older adult population, and this mechanism, if present, is potentially weakened due to cognitive slowing in aging. Future research utilizing consistent methodology, especially in terms of consistency in experimental tasks, is needed to solidify findings for acute exercise effects on processing speed in older adults.

Effect of Acute Exercise on Inhibitory Control

Studies examining the effect of acute exercise on inhibition have had mixed results. We hypothesized that older adults would show improved inhibition as a result of the acute exercise condition based on research consistent with the inhibition theory of exercise (Lambourne & Tomporowski, 2010). Our alternative hypothesis was that exercise effects on inhibitory control may not be able to overcome age-related decline in inhibition (Dempster, 1992). Thus, no improvements on behavioral tasks of inhibitory control would be seen.

The results of the current study are supported by previous findings reporting no change in interference effect in older adults (Barella et al., 2010) a result of acute exercise. As previously mentioned, this study used a non-exercise control condition and measured inhibition using the Stroop task. Inhibition was calculated by examining reaction times of a Stroop Interference task that consisted exclusively of incongruent Stroop trials, and a Stroop Inhibition task that introduced negative priming by presenting target colors of incongruent trials that were the same as the distractor word in the previous trial. Task performance did not improve as a result of exercise, though a main effect of time was reported, indicating a practice effect for both tasks (Barella et al., 2010).

Previous findings of improved inhibitory control as a result of acute exercise in older adults do not support current study findings (Won et al., 2019b; Johnson et al., 2016; Lucas, Ainslie, Murrell, Thomas, Franz, & Cotter, 2012). Lucas et al. (2012) administered the Stroop task in separate trial sets deemed “easy” (congruent) and “difficult” (incongruent) blocks. They found improvement in the incongruent condition through shorter RTs during moderate intensity acute cycling. Although classic interference effect was not calculated, improved performance exclusively on incongruent trials as a function of exercise indicates improved inhibitory control. It must be noted that this study was cross-sectional in nature, meaning participants completed exercise and control conditions on the same day, and that the same tasks were used in both conditions, creating the possibility of a practice effect rather than exercise effect contributing to results. Johnson et al. (2016), reported improved inhibitory control (shorter RTs post-exercise compared to pre-exercise) using a Stroop Interference (SI) task that consisted exclusively of incongruent stimuli, similar to those used in our study. This study evaluated both resistance and aerobic exercise, though no non-exercise control condition was utilized. Therefore, it cannot be determined whether improvements in inhibitory control post exercise are true exercise effect or the result of practice effect. Finally, Won et al. (2019b) reported improved performance accuracy on congruent and incongruent trials, but not improved reaction time, on the flanker task after 30-40 minutes of cycling compared to a sedentary control task. Though interference effect, calculated from correct incongruent minus congruent trials, did not improve as speed did not improve, improved accuracy has implications for improved inhibitory control as a result of acute exercise. In our study, accuracy on the Stroop task did not significantly improve in the post session, though notably high accuracy scores in the pre session (averages 87% to 99%) did not allow much room for significant improvement.

In addition to variance in experimental tasks, variance in calculation of Stroop effect (interference effect), or lack of calculation of true interference effect, may contribute to the mixed nature of the literature. In the present study, Stroop effect was calculated by subtracting reaction times on incongruent trials from reaction times on neutral trials, as opposed to the traditional calculation method (incongruent minus congruent trials). Calculation of incongruent minus neutral trials provides a more precise measure (as facilitation effect is controlled for), but Stroop effect value will be smaller, and less likely to be statistically significant than with the traditional calculation. However, it is likely that if calculation of incongruent minus congruent trials yields significant results, this is a measure of facilitation rather than improved inhibitory control, as incongruent minus neutral trial calculation did not yield significant results.

Another possible contributor to lack of improved inhibitory control as a result of exercise is that the cognitive effects of exercise may not be strong enough to consistently overcome the reduced inhibitory control seen in healthy older adults (Dempster, 1992). Significantly slower RTs on congruent, incongruent, and neutral Stroop task trials in this study during comparison of old and young adult data support this notion. Based on current study findings and previously detailed supporting studies, acute exercise does not have substantial enough effects on inhibitory control in the older adult population to produce consistently replicable results. However, results must be interpreted with caution, as Stroop is just one task of cognitive control and the absence of exercise effect on this task does not definitively show that acute exercise does not improve cognitive control.

Effect of Acute Exercise on Lexical Processing

It was hypothesized that older adults would show improvements in lexical speed seen in younger adults (Faroqi-Shah et al., in prep), as well as improvements in lexical inhibition not seen in younger adults, as a result of exercise as lexical processing relies on speed (Indefrey, 2011) and a correlation has been documented between word retrieval and processing speed (Faroqi-Shah & Gehman, under review). The alternate hypothesis was that potential exercise effects may not be able to overcome age-related decline in lexical processing (Thornton & Light, 2006), and no exercise-induced improvements in lexical speed or inhibition would be seen in older adults. To our knowledge, this is the first research study that has evaluated the linguistic effects of physical exercise on neurotypical older adults. While acute exercise resulted in faster lexical decision response times in young adults (Faroqi-Shah et al., in prep), this lexical speed enhancement was not replicated with older adults in the Lexical Decision and Picture Verification tasks. Given that older adults had slower RTs than younger adults, it is possible that 25 minutes of acute exercise was insufficient to counter the lexical slowing seen with healthy aging. Therefore, the effects of a single bout of acute cycling on lexical processing in terms of speed and inhibition are nonsignificant in older adults. However, due to the lack of research in this area, future studies investigating acute exercise effects on language are needed in both young and old adults to solidify this claim.

Limitations and Future Directions

Before drawing final conclusions from this study, it is important to consider methodological limitations that may have influenced results. This study, like many previous studies examining acute exercise effects (Rattray and Schmee, 2013; O'Leary et al., 2011; Pontifex & Hillman, 2007; Davranche et al., 2006), utilized a within group repeated measures design. Future research in this realm should be conducted comparing an active and inactive group, such as the design used by Stones & Kozma (1989). Using an active experimental group and a sedentary control group would allow for use of a between-groups study design rather than a within-groups or repeated measures study design.

In a between-groups design, participants are divided into experimental and control groups. Thus, individuals do not complete experimental tasks on more than one occasion and likelihood of practice effect is greatly reduced. Robust practice effect was seen in the present study, as well as the original young adult study (Faroqi-Shah et al., in prep), despite use of four different versions of each experimental task. Furthermore, comparison of young and old data cycling revealed significant improvement of Stroop task performance in older adults compared to younger adults not seen in analysis of older adult data alone. This finding was interpreted as a stronger practice effect in older adults for this task rather than a true exercise effect. Due to the strong practice effect seen in the current study and previous studies of this nature (Barella et al., 2010; Faroqi-Shah et al., in prep), is important for future researchers to consider the possible influence of practice effect during study design and interpretation of results to ensure reported exercise effects exist above and beyond practice effect.

Another aspect of practice effect recorded in the literature is that of placebo effect. Researchers have reported concern for behavioral measures of cognition improving in the exercise condition because participants think they should, rather than because of true exercise effects (Kramer & Colcombe, 2018). In the present study, older adult reaction times were significantly slower in the video condition during pre and post sessions compared to the cycling condition for both the Pattern Comparison and Lexical Decision tasks. It is possible that these slower reaction times in the control condition were induced by the placebo effect. Future researchers should consider this possibility during interpretation of study findings. In addition to placebo effect, the condition effect seen in the Lexical Decision and Pattern Comparison tasks may been influenced by increased participant arousal on the day the exercise condition was administered. Specifically, heart rate (and thus arousal) may have been higher on the cycling day due to heightened anxiety or expectancy during explanation of the cycling condition. Unfortunately, baseline heartrate was not calculated during either the cycling or control condition, so it is not possible to identify any differences in heart rate present in this cohort.

Researchers have utilized affective scales such as the Hardy and Rejeski Feeling Scale (FS) to monitor participant attitudes related to acute exercise engagement (Rose & Parfitt, 2008; Reed & Ones, 2006). Positive affective response to exercise is required to establish future exercise behaviors and has been correlated to participant intensity during acute exercise. Specifically, exercise intensity has been reported to influence affective response, and affective response has shown to be a regulator of acute exercise intensity (Rose & Parfitt, 2008; Reed & Ones, 2006). It is possible that participant attitudes related to cycling could have influenced exercise intensity and exercise effects, though as we did not administer an affective scale, we are unable to examine this possibility in this cohort of participants.

Another factor to consider is whether the findings of this study could have been influenced by the fitness level of the participants. There is some evidence that fitness level may moderate the cognitive benefits of exercise (Hillman et al., 2006; Stones & Kozma, 1989, but see Etnier et al., 2006). Responses from the CHAMPS questionnaire (Stewart et al., 2001) indicated the participants in the current study had an average weekly exercise engagement of 12 hours (SD=7.8, range=3-32), which exceeds the World Health Organization (2020) recommendations of 2.5 hours per week for this age group. However, the CHAMPS Questionnaire (Stewart et al., 2001) is a measure of fitness behavior rather than a true physiological measure of fitness level, such as VO_2max, which was not calculated in this study. Calculation of VO_2max (Chang et al., 2014) would allow researchers to more definitively explore the influence of baseline fitness level on acute exercise effects.

Another recommendation to more precisely evaluate the effects of exercise on this population is to utilize more precise physiological measures, along with existing perceived measures (RPE) to determine individual participant exertion and ensure participants exert within the target range. In addition to calculating max heartrate and ensuring participants remain within 64%-79% max heartrate (CDC, 2019), calculation of physiological measures such as measurement of BDNF proteins pre and post exercise (Griffin et al., 2011), and use of neuroimaging such as fMRI to evaluate changes in blood flow and connectivity (Voss et al., 2019; Chang et al., 2015), could more precisely quantify exertion and potentially solidify the physical mechanism(s) by which exercise impacts cognitive and linguistic function.

Conclusions

In this experiment, neurotypical older adults (58-75) completed four computer tasks to evaluate the effects of acute exercise on processing speed, inhibitory control and lexical processing. In this group of community dwelling and moderately active older adults, acute exercise did not enhance processing speed, inhibitory control or lexical processing, beyond general practice effects. These findings are in contrast with those of younger adults, who showed improved processing speed and lexical speed as a result of twenty-five minutes of exercise. Older adults had slower response times than younger adults in all experimental tasks. There are two obvious interpretations of the findings: the effects of exercise, if any, are too subtle in older adults to emerge with twenty-five minutes of moderate intensity exercise. Neither arousal nor increased inhibitory control can be expected with an acute bout of cycling using the tasks in this paradigm, indicating that a single bout of acute exercise likely will not enhance rehabilitation effects in other adults with neurogenic cognitive or linguistic deficits.

Appendices

Appendix A

Comparison of Older and Younger Adult Video Data

Appendix A contains speed data from comparison of younger and older adult data for the video control condition.

Young and old group speed data three shared computer tasks – Reported in decimal values

Task	**Group**	**Video** ***(M, SD)***	**p-value (*****video group, time, group* time*****)**
Pattern Comparison	Young	Pre 752.542, 259.309 Post 703.352, 327.308	0.535, 0.000*, 0.090
	Old	Pre 1113.756, 646.968 Post 1040.422, 475.073	
Stroop Effect	Young	Pre 91.93, 95.847 Post 57.53, 34.36	0.067, 0.031*, 0.423
	Old	Pre 176.953, 186.351 Post 114.862, 101.392	
Lexical Decision	Young	Pre 1249.711, 256.250 Post 1198.490, 256.249	0.733, 0.000*, 0.321
	Old	Pre 1627.485, 446.276 Post 1564.125, 419.383	

**=statistically significant, p<.05*

Appendix B

Lexical Decision Task Stimuli

True Word Stimulus Items		**Nonword Stimulus Items**	
gasping	sucking	drilking	gitining
licking	lifting	bimering	befating
speaking	nodding	braping	vemming
winking	hitting	bekefing	kaneking
screaming	tickling	sorping	plabing
tying	chopping	flurping	flurping
holding	smirking	buting	plurping
knitting	peeling	biming	akolling
tickling	clutching	clarping	batising
talking	drawing	demaving	diviking
yelling	looking	bapping	tafading
drinking	poking	daroting	dafeshing
pinching	whispering	degaking	balimoting
frowning	talking	jilking	beeling
gripping	lifting	darkoring	jeeging
wiping	speaking	gapeting	bisobing
slapping	sniffing	kaneking	biveting
glancing	sighing	stipping	gelidding
stuttering	snatching	binasing	melping
washing	murmuring	pinoping	bogating
pinching	smiling	jilking	doding
folding	chewing	dibaming	pamusing
smirking	glancing	dasoging	blaiting
squinting	patting	blopping	daroting
nodding	writing	golaving	bumitting

snipping	hacking	kidaling	tafading
knocking	shrieking	baping	belosing
scratching	biting	drilking	fissing
knitting	frowning	binasing	golaving
wringing	sawing	puzing	preaming
weeping	grinning	daliding	garolling
digging	staring	dekising	plurping
scratching	sucking	lerping	felshing
chomping	lifting	kosofing	gitining

Appendix C

Picture Verification Stimuli

Practice Targets	**Presented Semantic Distractor**	**Object Targets**	**Presented Semantic Distractor**	**Action Targets**	**Presented Semantic Distractor**
sleep	yawn	milk	cream	shave	clean
drive	car	shark	ray	crash	
walk	run	bomb		eat	chew
car		chain	link	melt	
cook		chest		pray	
		wig	switch	kneel	rest
		crown		yawn	burp
		vase	jar	bounce	
		heel		pop	
		crab		float	float
		sword		cry	laugh
		cage	chamber	bite	sting
		hoof		paint	
		tank	warplane	plug	
		glove		wave	gesture
		horse		peel	strip
		bowl		beg	
		rain	downfall	dip	dunk
		sweat		trip	move
		bus		bow	
		clock	time	smell	feel
		doll		pinch	grip

fence		sew	
grapes		wink	gesture
gun		scare	
nail	fastener	mop	absorb
pear		dive	
pipe		cut	chop
clown		bite	chew
sun		crawl	walk
beard	hair	swing	sit
bell	ring	bark	utter
horse	donkey	clap	
fork	spoon	bounce	
glove		dance	move
mouse		read	
queen		laugh	
spoon		serve	
tree	grass	squeeze	
plant	root	write	communicate
cheese		fish	aquatic
wheel		lock	
tent	dwell	chain	ligament
bride		shave	
ant	bee	run	
bat	livestock		
egg			
frog	salamander		
lips	throat		
moon			

bell

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