The Role of Acute High-Intensity Interval Exercise as a Potential Facilitator for Improved Executive Functions and Affect in Healthy Young and Older Adults

by

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Author's declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

A single bout of aerobic exercise has been shown to improve executive functions and affect across the lifespan. The magnitude of improvements appear to be influenced by exercise-dependent factors, including the intensity and type of the exercise protocol. Recent studies have proposed that high-intensity exercise may elicit cognitive and mood improvements to a degree similar or greater than that of lighter intensities, especially when performed in an interval format. High-intensity interval exercise (HIIE) is a safe and time-efficient workout that may be an effective alternative to traditional endurance exercise. However, the influence of HIIE on executive functions and affect across age groups remains largely unknown. This study examined the effects of an acute bout of HIIE on two areas of executive function (inhibition and working memory) and affect among young and older adults.

A total of eight young adults and seven older adults completed the study. Using a repeated-measures design, participants completed three sessions: 1) baseline session: to determine fitness level and target heart rate (HR) for the HIIE intervention; 2) exercise session: HIIE intervention consisting of 10 x 1 min @ 80% heart rate reserve (HRR) interspersed with 1 min @ 40% HRR recovery; 3) control session: low-movement static stretching routine. Order of the experimental sessions (exercise, control) were counterbalanced. Executive functions were assessed immediately before, immediately after and 30-minutes following the cessation of the exercise and control interventions using a computerized Stroop task (inhibition) and a computerized n-back task (working memory). Response time and percent error were calculated from the cognitive task data, to establish a linear integrated speed-accuracy score (RT_{LISAS}). Affect was measured using the Physical Activity Affect Scale (PAAS) immediately prior to and following the completion of the experimental interventions. The four sub-scales of the PAAS (positive affect, negative affect, physical exhaustion and tranquility) were used in analysis. Participants also completed an online survey to identify the primary motivators and barriers for HIIE engagement.

Young adults showed a significant improvement in working memory immediately following the HIIE intervention, with improvements maintained into the 30-minute delay period. No significant improvements were observed in the control condition or during the tasks of inhibition. Older adults did not exhibit improvements in working memory or inhibition following the HIIE intervention compared to the control condition. Both young and older adults demonstrated enhanced simple information processing following HIIE, while no changes were observed in the control intervention. Young adults revealed improved exhaustion scores following HIIE and greater overall tranquility during the exercise session. Older adults did not exhibit changes in exhaustion or tranquility scores and no significant changes in negative or positive affect were observed among either group. Finally, young and older adults noted that the strongest motivators for HIIE engagement were physical health benefits, whereas a lack of time to exercise and confidence towards HIIE were the greatest barriers.

Results of this study suggest that an acute bout of HIIE may result in improved cognition and affect, but the magnitude of improvements may be dependent on age group and the specific domain of executive function being assessed. Findings should be interpreted with caution due to the small sample size of this study; however, future studies should continue to explore the potential of HIIE as an effective intervention to improve executive functions and affect across age groups, using the results, limitations and suggestions presented in this thesis.

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List of Abbreviations

HIIE . . . . High Intensity Interval Exercise

PFC . . . . Prefrontal Cortex

fMRI . . . . . . Functional Magnetic Resonance Imaging

CRUNCH . . Compensation-Related Utilization of Neural Circuits Hypothesis

WCST . . . . . Wisconsin Card Sorting Task

BDNF . . . . . Brain-Derived Neurotrophic Factor

IGF-I . . . . . . Insulin-Like Growth Factor

MCI . . . . Mild Cognitive Impairment

ACSM . . . . . American College of Sports Medicine

HRR . . . . . . Heart Rate Reserve

METS . . . . . Metabolic Equivalents

HR . . . . Heart Rate

VO$_2$ . . . . . . Oxygen Consumption

MICE . . . . . Moderate Intensity Continuous Exercise

fNIRS . . . . . Functional Near-Infrared Spectroscopy

EEG . . . . . . Electroencephalography

P3 . . . . P300 Wavelength

POMS . . . . . Profile of Mood States

PAAS . . . . . Physical Activity Affect Scale

COVID-19. . 2019 Novel Coronavirus

WRAP . . . . . Waterloo Research in Aging Participant Pool

CCCARE. . . (Waterloo) Centre for Community, Clinical and Applied Research Excellence

GAQ . . . . . . Get Active Questionnaire

MoCA . . . . Montreal Cognitive Assessment

GSA-15 . . . Short-Form Geriatrics Depression Scale

IPAQ . . . . . International Physical Activity Questionnaire

PASE . . . . . Physical Activity Scale for the Elderly

GXT . . . . . . Graded Exercise Test

ECG . . . . . . Electrocardiogram

RPE . . . . . . Rating of Perceived Exertion

RT_{LISAS} . . . . Linear Integrated Speed-Accuracy Score

SD . . . . Standard Deviation

RT . . . . Response Time

PE . . . . Percent Error

ANOVA . . . Analysis of Variance

η2G . . . . Generalized Eta-Squared

CHAPTER 1: INTRODUCTION

Canada's population is estimated to reach approximately 55 million by 2068, with one in every four Canadians being 65+ years of age by this time (Statistics Canada, 2020). The majority of seniors will experience some form of decline in cognition with aging, often becoming noticeable in certain cognitive domains by the 5th or 6th decade of life (Diamond, 2013; Kirova et al., 2015; Padgaonkar et al., 2017; Turner & Spreng, 2012). Executive functions are highly vulnerable to the effects of aging, with older adults often exhibiting significantly greater difficulty in tasks of executive function compared to young adults (Fjell et a., 2016; Wasylyshyn et al., 2011).

A growing body of literature has emerged within the past few decades focusing on the positive effects of exercise on the brain (Chang et al., 2012; Pontifex et al., 2019; Warburton et al., 2006). Within the literature, it is recognized that executive functions can be highly influenced by aerobic exercise (Chang et al., 2012; Northey et al., 2018). Meta-analyses have determined that, across all age groups (children to older adults), aerobic exercise elicits a small-to-moderate positive effect on executive functions both for acute (a single exercise bout) and chronic (an extended training period) exercise interventions (Chang et al., 2012; Colcombe & Kramer, 2003). Following a chronic aerobic exercise intervention, significant improvements in executive functions have been observed among both young and older adults (Colcombe & Kramer, 2003; Guiney & Machado, 2012). Acute aerobic exercise also elicits short-term improvements in executive functions across age groups, although these improvements are often greater for older adults, possibly due to a "ceiling" effect in young adults (Ludgya et al., 2016; Sibley & Beilock; 2007). The magnitude and duration of performance changes are variable and tend to depend on exercise-specific factors, such as the intensity and type of the acute exercise intervention (Dupuy et al., 2015; Tsukamoto et al., 2016).

Executive functions have shown greater improvements following moderate-intensity exercise compared to a low-intensity exercise protocol (Kamijo et al., 2009; Lucas et al., 2012). Less research has been conducted on the effects of high-intensity exercise, especially in older adults; however, studies have proposed that high-intensity exercise may improve executive functions greater or equal to that of lighter intensities, particularly when performed as intervals

(Gibala et al., 2012; Moreau & Chou, 2019; Tsukamoto et al., 2016). High-intensity exercise tends to be of a duration shorter than moderate or light exercise and can therefore be a more time-efficient alternative to traditional exercise protocols, while still benefiting cognitive and cardiovascular health (Gibala et al., 2012).

In addition to cognitive performance benefits, exercise has also been shown to improve other areas of mental well-being, including affect and mood (Basso & Suzuki, 2017; Hogan et al., 2013). Similar to executive functions, acute exercise has also been associated with short-term improvements of affect, with effects lasting up to 24 hours post-exercise regardless of age, fitness level, duration or intensity of exercise (Basso & Suzuki, 2017; Ekkekakis et al., 2011; Reed & Buck, 2009).

By engaging in high-intensity interval exercise (HIIE), short-term improvements in executive functions and mood may be stimulated, which can provide benefits for everyday living, such as enhanced planning skills, problem solving and creative thinking (Diamond et al., 2013; Voss et al., 2011). These benefits are especially valuable for older adults, who may experience cognitive decline in these areas (Diamond et al., 2013; Voss et al., 2011). To the best of the authors knowledge, no published study has compared the influence of acute HIIE on multiple areas of executive functioning among both young and older adults. This study will help to identify and compare exercise-induced changes in executive functions and affect between young and older adults. By doing so, strategies targeted towards improving brain health can be better informed on the multifaceted benefits of HIIE, which may be mediated by age-specific differences.

CHAPTER 2: LITERATURE REVIEW

2.1 Cognition and Executive Function with Aging

2.1.1 Introduction to Cognition & Executive Functions

Cognition encompasses a range of mental processes that are constantly being updated and developed based on experience and comprehension. These processes are responsible for the recognition of knowledge and the development of intellectual skills, therefore allowing for humans to engage in both complex and simple tasks. Simple tasks often involve lower-order processes, such as perception, whereas complex tasks (e.g., a problem-solving challenge) require higher-order cognitive domains, including executive functions (Luna, 2009; Reigeluth & Moore, 2009).

Executive functions allow for voluntary control of goal-driven behaviour (also known as “cognitive control”) (Luna, 2009). These advanced functions are important for problem-solving, purposeful thought and selection of appropriate action, which are essential skills for the growth and success of an individual (Diamond, 2013; Zelazo, 2004). Executive functions are highly sensitive and may be influenced by multiple factors. For example, declines in executive functions are commonly observed among older adults throughout the aging process, whereas executive function improvements have been observed with short-term and long-term exercise engagement (Guiney & Machado, 2012; Padgaonkar et al., 2017). While there is some disagreement regarding the components of executive functions, many agree on three core executive functions: inhibition, working memory and cognitive flexibility (Diamond, 2013).

Inhibition (also termed as “inhibitory control”) is the ability to ignore an instinctive or automatic reaction toward a stimulus in order to choose a response that is more suitable for the task at hand. Inhibition allows humans to act against impulse and make an appropriate decision instead of choosing a more unconscious course of action (Diamond, 2013). While it is not usually considered executive function, selective attention is complimentary to inhibition. Selective attention allows for the allocation of processing resources towards the relevant stimuli, in order to maintain focus. Therefore, when faced with a distracting task or environment, inhibitory control and selective attention often work simultaneously (Booth et al., 2003).

Working memory involves holding information in the mind - that is, information that was previously provided but is no longer present. This information can then be retained and manipulated to plan future behaviour (Luna, 2009). Working memory is necessary for building upon any mental activity that takes place over time, such as updating information, considering alternative actions, or connecting new concepts with previously learned ideas (Diamond, 2013).

Cognitive flexibility is believed to build upon inhibition and working memory (Diamond, 2013). By inhibiting a previously held perspective or reaction, a new response can be created that enables an individual to approach the task demand using a different strategy. These core executive functions are the foundation for other higher-order functions that assist in goal-directed behaviours, such as reasoning, problem solving and planning (Collins & Koechlin, 2012; Diamond, 2013).

Executive functions are dependent on a widely distributed range of extended networks throughout the brain, such as the hippocampus, amygdala, striatum, posterior parietal cortex and the prefrontal cortex (PFC) (Girotti et al., 2018; Holmes & Wellman 2009). It is generally believed that the PFC plays a primary role in the regulation of executive functions, as it has been noted as a critical contributor to the coordination and initiation of these processes (Diamond, 2013). The dorsolateral PFC is thought to participate in decision making, planning and working memory, whereas the ventromedial PFC contributes to the expression and control of emotional behaviours, thus influencing inhibitory control (Ardila, 2008; Menon, 2011).

2.1.2 Executive Functions across the Lifespan

Executive functions improve from childhood to young adulthood, in part due to the maturation of cortical structures and networks. Between infancy to adulthood, there is a vast growth of grey matter (nerve cell bodies) and white matter (myelinated nerve fibers) that result in an increase of brain size by four or five-fold (Craik & Bialystok, 2006). This development of network structures may also lead to a change in the neural areas recruited during cognitively challenging tasks. Konrad et al. (2005) used functional magnetic resonance imaging (fMRI) to measure the level of brain activation in both children and adults during an executive attention task. Children exhibited significantly worse performance accompanied by less neural activation in the cortical areas commonly recruited by adults, while simultaneously recruiting additional regions in the brain (Konrad et al., 2005). This finding suggests a possible specialization of neural circuits during normal development, leading to a more definitive and efficient network that is well-established by young adulthood (Konrad et al., 2005; Luna, 2009). Once the integration of cortical networks has been established in adulthood, young adults are able to exhibit heightened executive performance that allows for greater inhibitory control, less interference from distractors and improved working memory compared to those younger (children) and older (elderly) than themselves (Luna et al., 2009).

During later life, the efficiency of executive functions begins to degrade (Grady, 2012; Padgaonkar et al., 2017; Turner & Spreng, 2012). While the rate of decline of these processes is highly variable across individuals, a significant decline is common after the age of 60 years (Andres et al., 2008; Diamond, 2013; Wasylyshyn et al., 2011). Neuroanatomical changes, such as the deterioration of grey and white matter in the brain, lead to the reduction of cortical integrity and volume. This effect of age-related brain atrophy is commonly seen in the frontal lobes and can highly influence the simultaneous connections between the PFC and other cortical areas required for efficient regulation of executive functions (Fjell et al., 2016; Sasson et al., 2013). As a result, executive functions are highly vulnerable to age-related cortical deterioration (Townsend et al., 2006; Turner & Spreng, 2012).

A decline in inhibitory control is often observed during late adulthood, as demonstrated by performance on tasks such as the Stop-Signal and Stroop tasks (Andres et al., 2008; Colcombe et al., 2005; Coxon et al., 2014). Compared to young adults, older adults are often less able to inhibit irrelevant visual and auditory stimuli, resulting in decreased performance (Diamond, 2013; Gazzaley et al., 2005). The Stroop task is a common inhibitory test that requires participants to name the color of the ink in incongruent and congruent conditions. The incongruent condition requires inhibition of the predominant stimulus (reading of the word) allowing participants to instead name the ink colour. Some studies have observed greater and more diffuse activation patterns in cortical areas related to inhibitory control (e.g., premotor, dorsolateral and ventrolateral PFC areas) among older adults compared to young adults (Langenecker et al., 2004; Neilson et al., 2002).

The finding of increased and distributed cortical activation patterns suggests a possible compensatory strategy, potentially due to atrophy in the primary neural pathway that results in the "delateralization" of brain activation in the PFC (Martins et al., 2015). By adjusting the pattern of brain activity, new brain networks may be bilaterally recruited by older adults in an attempt to maintain task performance (Martins et al., 2015; Steffener et al., 2009). Although older adults that demonstrate this compensatory pattern of activation still tend to perform more poorly on high-level tasks of inhibition than young adults, studies have shown that older adults who recruit bilaterally often perform better on tasks of executive function compared to older adults who do not exhibit this pattern of bilateral activation (Langenecker et al., 2004; Martins et al., 2015; Reuter-Lorenz & Park, 2010). It is important to note that neural activation patterns are highly task-specific. Therefore, older adults may exhibit cortical under-activation, over-activation, or diffuse neural activity patterns that can vary significantly, depending on the task demands and the individual (Coxon et al., 2014; Turner & Spreng, 2012).

Many researchers believe that one's capacity for inhibition influences working memory, as a lower inhibitory control may cause individuals to become more vulnerable to attentional interference and distraction (Diamond, 2013). This inability to ignore task-irrelevant information may result in an overloading of cognitive resources in older adults and thus lower the efficiency of working memory during a cognitive task (Diamond, 2013; Padgaonkar et al., 2017).

Working memory performance can be measured during the n-back task, a popular working memory task. Stimuli (e.g., numbers or letters) are presented one at a time and participants are required to indicate if the current stimulus matches the one seen *n* items previously. The 0-back and 1-back tasks are less demanding, as they require participants to respond to an unchanging "target" item (0-back, equivalent to a response time task) or to the immediately preceding stimulus (1-back). On the other hand, the 2-back and 3-back tasks demand a more continuous and complex updating of information (Hogan et al., 2013; Mattay et al., 2006). Compared to young adults, older adults have shown similar performance scores but greater neural activity in the PFC during the 1-back task. Conversely, lower PFC activity has been observed during the 2-back and 3-back tasks among older versus young adults, with an associated decline in working memory performance (Heinzel et al., 2014; Mattay et al., 2006; Wang et al., 2019).

The abovementioned findings are in line with the Compensation-Related Utilization of Neural Circuits Hypothesis (CRUNCH), which suggests that both young and older adults will generally over-activate cortical regions as task difficulty increases; however, older adults tend to exhibit brain over-activation at much lower difficulty levels compared to young adults due to age-related declines in neural connectivity (Reuter-Lorenz & Cappell, 2008) As task difficulty increases, older adults tend to exceed their cognitive resource “limit” and are unable to maintain the brain overactivation patterns, thus resulting in a task performance decline and under-activation of the brain (Grady, 1998; Martins et al., 2015; Mattay et al., 2006; Reuter-Lorenz & Cappell, 2008). During tasks requiring a higher cognitive load, working memory may therefore decrease as a result of a lowered capacity to store and process information with age (Kirova et al., 2015; Mattay et al., 2006).

The final of the three core executive functions, cognitive flexibility, also shows a decline with age (Collins & Koechlin, 2012; Diamond, 2013). Cognitive flexibility allows for an individual to quickly adjust their thoughts and actions in response to a changing environment (Rende, 2000). Tasks that involve changing demands tend to challenge the brain’s ability to mentally process and shift strategies. An example of this includes sorting cards based on constantly changing rules (e.g., shape, color, number, etc.) as commonly seen in the Wisconsin Card Sorting task (WCST) (Johnco et al., 2013; Rende, 2000). Performance on the WCST (as measured by number of errors committed and categories achieved) tends to be worse among older adults compared to young adults and shows sensitivity to age, where the oldest age groups achieve the lowest scores (Rhodes, 2004).

Similar to inhibition, cognitive flexibility may also be influenced by working memory (Hartman et al., 2001). During many tests of cognitive flexibility, the participant must remember and update the information provided to them to respond accurately to the switching demands. Performance will decline if the participant cannot store information and/or recall the information from working memory (Hartman et al., 2001; Rhodes, 2004). Therefore, there is significant interconnectedness among executive functions that may exaggerate deficits in each domain when more than one process is affected (Kirova et al., 2015; Rhodes, 2004; Sasson et al., 2013).

2.2 Influence of Exercise on Executive Functions

It is widely believed that executive functions are more sensitive to the effects of exercise compared to lower-level cognitive or motor functions (Guiney & Machado, 2012). Positive exercise-linked improvements in executive functions have been observed among various populations, including children (Tomporowski et al., 2011), young adults (Hillman et al. 2008), healthy older adults (Diamond, 2013; Guiney & Machado, 2012) and clinical populations (Colcombe & Kramer, 2003; Scherder et al., 2005). Several exercise modalities have been examined in relation to cognition (e.g., aerobic, resistance, flexibility and neuromotor activities); however, aerobic exercise has been studied most often, perhaps due to the popularity and acceptability of aerobic exercise modalities (e.g., walking, biking, running) within the general population (Pontifex et al., 2019; Northey et al., 2018). Aerobic exercise has been associated with improved cognition, as well as enhanced structural and functional changes in the brain (Pontifex et al., 2019; Hillman et al., 2008).

2.2.1 Influence of Chronic Exercise on Executive Functions

An increasing amount of research has suggested a positive effect of chronic aerobic exercise on cognition in multiple meta-analyses (Colcombe & Kramer, 2003; Etnier et al., 1997; Northey et al., 2018). Colcombe and Kramer (2003) determined that aerobic fitness training had a moderate effect ($d = 0.48$) on cognition among the older adult population compared to a control group. Similarly, a recent meta-analysis of randomized control trials determined that exercise training elicited a small overall positive effect on cognitive performance in older adults (0.28) (Northey et al., 2018). Fewer analyses have focused on chronic exercise and cognition in young adults; however, chronic exercise has been shown to elicit a small effect (0.25) on cognition across the lifespan, from ages 6-90 (Etnier et al., 1997).

Executive functions are often identified as the cognitive domain most influenced by aerobic exercise (Colcombe & Kramer, 2003). Following a chronic exercise intervention, performance on tasks of cognitive flexibility (as measured by response time and accuracy) have been positively associated with exercise engagement in older adults, although these findings are inconsistent among young adults (Northey et al., 2018; Verburgh et al., 2014). Both young and older adults have shown significant improvements in working memory and inhibitory control from pre- to post-chronic exercise intervention, with inhibitory control often displaying the strongest improvement (Colcombe & Kramer, 2003; Guiney & Machado, 2012; Prakash et al., 2011). When measuring the effects of habitual exercise on executive functions, comparisons are commonly made between sedentary and active adults, or those of a low and high fitness level. Among both young and older adults, higher levels of cardiovascular fitness have been associated with increased inhibitory control (Dupuy et al., 2015), attention and working memory (Newson & Kemps, 2008) compared to lower levels of fitness.

Improvements in executive functions seem to be underpinned by exercise-related structural and functional changes in the brain. Cross-sectional studies comparing fitness levels and brain structure have found that greater fitness levels are associated with larger hippocampal volume (Erikson et al., 2009), higher grey matter density in the frontal, temporal and parietal cortices (Gordon et al., 2008), less age-related atrophy in the prefrontal and temporal cortices (Colcombe et al., 2003) and enhanced resting cerebral blood flow (Ainsile et al., 2008). The differences between high and low fit groups are more substantial among older adults, perhaps because this group is highly susceptible to age-related cortical changes (Erickson & Kramer, 2008; Voss et al., 2011). However, fit young adults also exhibit increased cerebral oxygenation during tasks of executive function, with a positive association found between cerebral oxygenation and inhibitory control (Dupuy et al., 2015). Additionally, higher fitness levels in young adults have been linked to greater gray matter volume and enhanced memory recall (Whiteman et al., 2016).

Fitness-related cortical changes are certainly not exclusive to life-long athletes and a number of adaptations have been observed following relatively short-term engagement in exercise interventions (3-24 month duration) (Firth et al., 2018; Guiney & Machado, 2012; Rathore & Lom, 2017). Compared to a control group, older adults who completed six months of aerobic training had an increase of gray matter in the PFC (Colcombe et al., 2003). Erikson et al. (2011) observed an increase in hippocampal volume after one year of aerobic exercise; the aerobic group showed a 7.78% improvement in cardiovascular fitness and a 2% increase in size of both the left and right anterior hippocampus. Conversely, the control group had no significant change in fitness level, accompanied by an average decrease in size of the hippocampus of 1.4%. The magnitude of increase in hippocampal volume was correlated with the magnitude of improvement in memory performance on a spatial memory task (Erickson et al., 2011). It is important to note, however, that changes in brain structure are not consistently noted across all studies and further research is needed to determine the specific individual factors that influence cortical adaptations (Hillman et al., 2008).

The mechanisms responsible for improvements in cognitive performance and brain structure with chronic aerobic exercise have not yet been fully elucidated but are likely to involve: neurotrophic factors (e.g., brain derived neurotrophic factor [BDNF]), neurogenesis, synaptogenesis, changes in hormonal regulation and cerebral blood flow (Ainsile et al., 2008; Gligoroska & Manchevska, 2012; Guiney & Machado, 2013; Marmeleira, 2013). Aerobic exercise is associated with higher levels of BDNF, which has been linked to the creation and survival of neurons (most commonly within the hippocampus) and better learning and memory performance in humans and animals (Erikson et al., 2011; Gligoroska & Manchevska, 2012). Exercise also influences hormonal release of compounds that are believed to regulate BDNF, such as insulin-like growth factor-I (IGF-I), corticosteroids and estrogen. These hormones may increase the availability and integrity of BDNF, further aiding in neurogenesis and synaptogenesis (Gligoroska & Manchevska, 2012; Llorens-Martín et al., 2008). Finally, chronic aerobic exercise has been shown to increase blood flow to the brain at rest and during exercise (Ainsile et al., 2008). This increase may help to improve brain metabolism and neural efficiency by enhancing cerebral energy stores through oxygen and glucose delivery (Marmeleira, 2013).

2.2.2 Influence of Acute Exercise on Executive Functions

A single session of aerobic exercise (termed “acute” aerobic exercise) has been shown to elicit short-term improvements in cognitive performance, depending on a wide range of exercise- and population-dependent factors (Chang et al., 2012). Generally, there appears to be a small positive effect of acute exercise on cognition, with overall effect sizes from meta-analyses ranging from 0.10 (Chang et al., 2012) to 0.20 (Lambourne & Tomporowski, 2010). Literature focusing on acute exercise and executive functions tends to study inhibition the most frequently (Chang et al., 2012; Pontifex et al., 2019). Of the three components of executive function, inhibition often shows the largest improvement following a bout of acute exercise (Pontifex et al., 2019). Verburgh et al. (2013) found that acute exercise had a relatively consistent small-to-moderate effect on inhibition for young adults ($d = 0.42$), whereas working memory had far more inconsistent findings among this age group ($d = 0.05$). However, the results of individual studies are often hard to compare, as the influence of exercise on each executive function is likely mediated by other factors as well, such as: the population cohort, the time of cognitive assessment and exercise intensity (Pontifex et al., 2019).

2.2.2.1 Moderation by Age

Acute exercise studies involving young adults have often found significant but small improvements in executive functions. A meta-analysis by Chang et al. (2012) determined that, out of 79 studies that measured cognitive performance after acute exercise, only six studies included participants aged 60 years or older while 42 studies involved those aged 20-30 years. The lack of research has made it difficult to draw solid conclusions for the older adult population, whereas a number of reviews and meta-analyses exist for young adults (Chang et al., 2012; Ludyga et al., 2016; Moreau & Chou, 2019).

Following a bout of aerobic exercise, young adults have demonstrated improved executive functions, including greater inhibitory control (Ferris et al., 2007; Kao et al., 2017) better cognitive flexibility (Dupuy et al., 2018) and enhanced planning and problem solving (Chang et al., 2011) when compared to a control group. However, measures of working memory have been more inconsistent among the young adult population, as some studies have shown improvement (Weng et al., 2015), with others showing non-significant changes from pre- to post-exercise (Verburgh et al., 2013). When measured after exercise, speed of response in a working memory task among young adults commonly improves, but the accuracy rate is often worse (Li et al., 2014; Sibley & Beilock, 2007) This may be a result of a significant speed-accuracy trade-off, or a post-exercise increase in neural “noise” (i.e., neurotransmitters and hormones) that may have a negative effect on accuracy while also increasing processing speed (McMorris et al., 2011).

Although studies comparing young and older adults are limited, acute aerobic exercise has been shown to have a stronger positive effect on executive functions in older adults compared to young adults (Chang et al., 2012; Ludgya et al., 2016). It is possible that persons facing age-related declines in cognition may experience greater benefits from an aerobic exercise session compared to those who are cognitively healthy. Since executive functions seem to reach their maximum performance levels during young adulthood, there may be limited room for improvement (called a “ceiling effect”) for most young adults, compared to a larger cognitive variance among the older adult population (Ludgya et al., 2016; Sibley & Beilock; 2007).

Acute exercise may therefore provide greater benefit to those with lower baseline cognitive scores, as these individuals have shown a more significant improvement following exercise, compared to those with higher baseline scores (Sibley & Beilock, 2007). However, it is unknown if improvements of executive function may be mediated by the magnitude of cognitive decline (Tsai et al., 2018). Although individuals with mild cognitive impairment (MCI) have exhibited improvements in inhibitory control following acute aerobic exercise compared to a control group with MCI (Tsai et al., 2018), little research has been conducted to compare the effects of exercise in heathy older adults and older adults with MCI. Nonetheless, healthy older adults commonly show post-exercise improvements in the response time of inhibition and memory tasks (Alves et al., 2012; Hyodo et al., 2012) and greater sustained and selective attention (Peiffer et al., 2015) compared to a control group of a similar age.

2.2.2.2 Moderation by Exercise Intensity

The American College of Sports Medicine (ACSM) quantifies light, moderate and high intensities in multiple ways, including heart rate reserve (HRR), metabolic equivalents (METS), heart rate (HR) and oxygen consumption (VO_2) (American College of Sports Medicine, 2018). In the current review, HRR will be used as the primary indicator of exercise intensity, as it takes into account an individual’s resting and maximal heart rate, allowing for an accurate estimation of their target heart rate at a given intensity (HHR = % of target intensity (HRmax – HRrest) + HRrest). Light, moderate and high intensities correspond to 30-39% HRR, 40-59% HRR and 60-89% HRR, respectively, and all levels of intensity have been used in the recent exercise-cognition literature (American College of Sports Medicine, 2018; Chang et al., 2012; Pontifex et al., 2019).

Most researchers have used moderate-intensity exercise as their primary exercise protocol, although an increase of interest towards higher intensity exercise has grown exponentially within the past decade (Chang et al., 2012; Pontifex et al., 2019). The inverted-U hypothesis suggests that optimal improvements in cognitive performance will occur with moderate-intensity exercise, whereas smaller improvements, or even performance decrements, will be seen with light and vigorous intensities (Hung et al., 2013; Tomporowski, 2003). From this perspective, exercise is seen as a stressor where individuals would perform worse in a very low-arousal environment from lack of resources (e.g., decreased attention, muscle activation), as well as in a very high-arousal environment from an overload of resources (e.g., increased concentration of hormones, high fatigue state). Light-to-moderate-intensity exercise has therefore been proposed as the ideal intensity for cognitive improvement during exercise (Brisswalter et al., 2002; McMorris et al., 2011). The inverted-U hypothesis is primarily focused on arousal levels during exercise and is therefore not well-validated when cognitive performance is tested following exercise. As a result, hypotheses related to post-exercise cognitive performance often do not align with the inverted-U hypothesis.

Researchers have sometimes compared two or more intensities within a single study, commonly involving either light and moderate, or moderate and high-intensity exercise protocols (Kamijo et al., 2009; Kao et al., 2018; Mekari et al., 2020; Tsukamoto et al., 2016). During tasks of inhibition (e.g., Flanker and Stroop tasks) both young and older adults have exhibited greater improvements in processing speed and response time following moderate-intensity exercise, compared to light exercise (Kamijo et al., 2009; Lucas et al., 2012). Compared to rest, similar improvements following moderate-intensity continuous exercise (MICE) and HIIE have been observed for response time and inhibitory control during the Flanker task, as well as in short term-memory during a free recall task (Kao et al., 2018). Tsukamoto et al. (2016) also reported equal improvements in Stroop task response time during all three conditions (congruent, neutral, and incongruent) immediately following both MICE and HIIE, compared to a rest condition.

Although the results of comparative studies have generally shown similar improvements in cognitive performance between moderate and high-intensity exercise immediately following the exercise intervention, the relative effects appear to be highly dependent on the study protocol (Brisswalter et al., 2002; Pontifex et al., 2019). Although moderate-intensity studies will commonly use a continuous exercise protocol, this is not always the case for higher intensity exercise (Chang et al., 2012; Ludyga et al., 2016). High-intensity exercise that is prolonged and continuous can result in a reduction of executive functioning, possibly due to dehydration or extreme fatigue (Chang et al., 2012; Moore et al., 2012). The observed performance decrements include decreased inhibitory control, lowered working memory and increased errors (Moore et al., 2012; Tomporowski et al., 2007). As a result, it has been suggested that high-intensity exercise may be more beneficial if performed as intervals, with brief periods of vigorous activity interspersed with periods of active rest (Gibala et al., 2012). A high-intensity interval protocol may reduce possible physical and mental decrements that can accompany prolonged vigorous activity, while still inducing the physiological benefits of high-intensity exercise (e.g., enhanced cardiovascular fitness, secretion of growth hormones and muscle oxidative capacity) (Gibala et al., 2012; Gibala & McGee, 2008; Swain & Franklin, 2006).

2.2.2.3 Interaction of Time of Assessment & Exercise Intensity

The effects of acute aerobic exercise on executive functions can be significantly influenced by the timing of the cognitive assessment alongside the exercise intensity. These two variables (intensity and time of assessment) are often intermixed within the methodology of studies and their interaction can directly affect the performance of executive functions (Pontifex et al., 2019).

During exercise, greater performance scores have been noted with light or moderate-intensity exercise, compared to higher intensities (Chang et al., 2012; Mekari et al., 2015). This may be a result of the dual-task environment that arises when an individual engages in two tasks at once, increasing cognitive demands (Brisswalter, 1995). Improvements during exercise are generally noted during tasks that target lower-order processes (e.g., a simple response time test) versus complex tasks of executive function, or when exercise intensity is light. (McMorris et al., 2011; Mekari et al., 2015; Tomporowski, 2003). Mekari et al. (2015) observed a significant decrease in response time and accuracy scores in the Stroop task during high-intensity exercise (85% peak power output) compared to lower intensities (40% and 60% peak power). This decrease in performance was seen in both the executive and non-executive (congruent) conditions of the Stroop task (Mekari et al., 2015).

Immediately following exercise, comparison studies have found similar improvements in executive functions with exercise at various intensity levels (Peiffer et al., 2015; Tsukamoto et al., 2016). Compared to rest, both moderate and high-intensity exercise elicits significant post-exercise improvements in inhibitory control during the Flanker task among young (Tsukamoto et al., 2016) and older adults (Peiffer et al., 2015). Stroop task response time in the congruent and incongruent conditions has also displayed equal enhancements following moderate and high-intensity exercise (Ferris et al., 2007; Tsukamoto et al., 2016). The majority of evidence has supported the notion that exercise exhibits a positive effect on executive functions (most notably, inhibition) when measured immediately post-exercise across multiple intensity levels (Chang et al., 2012; Pontifex et al., 2019).

With a delay after exercise, greater improvements and/or better maintenance of inhibitory control has been observed following high-intensity exercise compared to lighter intensities (Kao et al., 2018; Tsukamoto et al., 2016). Tsukamoto et al. (2016) noted similar improvements among young adults in inhibitory control (as measured by response time) immediately following exercise in both HIIE and MICE groups; however, these improvements were only maintained in the HIIE group whereas scores returned to baseline in the MICE group. A similar study by Kao et al. (2018) also found greater improvements in response time and accuracy scores among young adults during an inhibitory task in the HIIE condition compared to the MICE condition following a delay. Less is known about the influence of HIIE on other areas of executive functions (working memory, cognitive flexibility) following a delay period, or about the influence of age (e.g., young vs older) on these effects (Chang et al., 2012; Moreau & Chou, 2019). Taken together, previous literature suggests that acute HIIE can result in improvements of executive functioning, but the specific age-dependent or domain-specific factors that may influence cognitive improvement is still unknown.

2.2.2.4. Possible Mechanisms

The mechanisms behind acute changes in executive function following exercise are not yet known; however, the increased expression of BDNF may facilitate cognitive improvements. BNDF has been identified in a range of cortical areas, including the cortex, hippocampus and basal forebrain – all of which are regions utilized during the performance of executive functions (Llorens-Martín et al., 2008). Through the measurement of BDNF levels in blood plasma and serum, several studies have found that BDNF concentration tends to be exercise-dependent (Ferris et al., 2007; Saucedo Marquez et al., 2015). Ferris et al. (2007) observed an increase in the level of serum BDNF following exercise, with the greatest increase following a maximal exercise protocol and a smaller, yet still significant increase following high-intensity exercise (30% and 13% increase from baseline, respectively); moderate-intensity exercise did not elicit a significant change in BNDF levels. In knowing that BDNF is a neuroprotective protein, it is possible that increased levels of BDNF may be observed following higher-intensity exercise as a type of “survival response”. Multiple studies have determined that high-intensity exercise produces greater levels of lactate alongside a larger increase in serum BDNF compared to lower intensity protocols (Ferris et al., 2007; Saucedo Marquez et al., 2015). As an increase in lactate represents the limited availability of oxygen in the body during higher intensity exercise, BDNF levels may therefore increase to temporarily “protect” the brain from the perceived danger of hypoxia. Functional near-infrared spectroscopy (fNIRS) studies have also discovered a decrease in cerebral oxygenation levels (compared to baseline) during vigorous exercise, providing further support towards the presence of limited oxygen availability during high-intensity exercise (Mekari et al., 2015; Rooks et al., 2010). However, the relationship between lactate concentration, oxygen availability and BDNF levels is not well-researched and many findings are inconclusive (Rojas Vega et al., 2006; Saucedo Marquez et al., 2015).

The influence of exercise on neural activity has been supported by electroencephalography (EEG) studies, through the analysis of the P300 (P3) wavelength (Kamijo et al., 2007; Kao et al., 2018; O’Leary et al., 2011). The P3 wavelength is an event-related potential that is evoked during the decision-making process and has displayed an increase in amplitude following moderate-intensity exercise, alongside a decrease in latency following both moderate and high-intensity exercise (Hillman et al., 2003; Kamijo et al., 2007; Kao et al., 2018). During challenging tasks of inhibitory control, P3 latency has displayed a decrease of a greater degree following high-intensity compared to moderate-intensity exercise (Kao et al., 2018). P3 amplitude and latency are believed to reflect neural activity levels and information processing speed, respectively (De Beaumont et al., 2007). Therefore, it has been suggested that P3 latency may be more sensitive to task difficulty, requiring greater executive control processes to enhance the speed of neural processing. This process may be facilitated by exercise intensity, although more research is needed to determine a conclusive hypothesis (Kamijo et al., 2007; Kao et al., 2017).

2.3 Exercise-Related Changes in Affect

The benefits of exercise have been shown to extend into other areas of mental well-being, including affect (Basso & Suzuki, 2017; Hogan et al., 2013). Affect is a measure of one’s short-term emotional experience that lies on a continuum from positive to negative, as well as low-activation to high-activation. For example, excitement would equate to a positive-high activation state, whereas depression would reflect a negative-low activation state (Lox, 2000; Reed & Buck, 2009).

Various instruments have been used to determine the influence of exercise on affect, including the Profile of Mood States (POMS) questionnaire (McNair et al., 1981), the Felt Arousal Scale (Svebak & Murgatroyd, 1985) and the Physical Activity Affect Scale (PAAS) (Lox et al, 2000). The PAAS is a validated measure that has gained popularity over the past few decades due to its inclusion of four-subscales (positive affect, negative affect, exhaustion, and tranquility) that have been shown to be highly sensitive to the effects of exercise (Bryan et al., 2007; Carpenter, 2010). The use of the PAAS, along with other self-report questionnaires has allowed researchers to identify the specific areas of affect that are most influenced by aerobic exercise - both in relation to chronic and acute exercise participation.

Chronic engagement in aerobic exercise has been positively associated with improved emotional behaviour and affect, including more frequent positive emotions, less frequent negative emotions and heightened optimism compared to sedentary individuals (Bernstein et al., 2019; Bernstein & McNally, 2018). Aerobic exercise programs have also been recommended to help reduce anxiety and depression among both young and older adults in healthy and clinical populations (Morgan et al., 2013; Stănescu & Vasile, 2014; Ströhle, 2009). Although improvements in affect have been observed following relatively short exercise programs (4-6 weeks), programs lasting 10-12 weeks have been found to produce the greatest improvements in long-term changes in affect (Reed & Buck, 2009).

An acute bout of exercise has been shown to improve one’s affective state (increased positive affect, decreased negative affect) regardless of age, fitness level, duration or intensity of exercise (Basso & Suzuki, 2017; Ekkekakis et al., 2011; Reed & Buck, 2009). Improvements in affect can occur immediately post-exercise, with effects persisting for up to 24 hours following the cessation of exercise. However, there is no one-size-fits-all approach to improving affect through acute exercise, as the type of affective response tends to be influenced by inter-individual factors (Basso & Suzuki, 2017).

According to multiple meta-analyses, affective change can be highly dependent on the relationship between fitness level and exercise intensity (Basso & Suzuki, 2017; Ekkekakis et al., 2011). Individuals of all fitness levels can experience exercise-related improvements in affect; however, this is likely specific to the type of exercise most appropriate for each fitness level. Studies have shown that participants of a lower fitness level will have a more positive affective experience with a lower intensity exercise intervention compared to highly-fit individuals, whereas affective improvements are greater with a moderate-to-vigorous exercise intervention among those of a higher fitness level (Carpenter, 2010; Reed & Buck, 2009).

When comparing the changes in affect and enjoyment between an acute bout of HIIE versus MICE, the findings have been mixed. In both active and inactive participants, HIIE has been shown to elicit similar or greater levels of enjoyment compared to MICE; however, there is often not a positive correlation between enjoyment levels and positive affect (Jung et al., 2013; Oliveira et al., 2013; Thum et al., 2017). A study by Jung et al. (2013) examined the affect and enjoyment levels of HIIE, MICE and continuous high-intensity exercise among inactive participants. Participants rated HIIE as the most enjoyable exercise of the three interventions, but MICE produced greater affective scores compared to HIIE. Similarly, HIIE has produced higher enjoyment levels compared to MICE in active participants, but affective scores in the HIIE group tended to be lower than those in the MICE group (Oliveira et al., 2013; Thum et al. 2017). It is very important to note, however, that affect is often measured during the exercise intervention and not following the cessation of exercise, which may influence the interpretation of the findings due to increased fatigue and anxiety often observed during higher intensity protocols (Ekkekakis et al., 2011; Oliveira et al., 2013; Thum et al., 2017).

Positive changes in enjoyment and affect after exercise may improve motivation to exercise (Ekkekakis, 2011; Reed & Buck, 2009; Schwerdtfeger et al., 2010). However, exercise participation is also influenced by a multifaceted set of factors that can impact exercise participation, including psychological, physical and environmental elements, which tend to vary depending on a person's age and life experiences (Allender et al., 2006; Hardcastle & Taylor, 2001). Identifying the perceived supports and barriers – and the level to which they impact exercise engagement – can aid in improving health promotion efforts, leading to increased exercise participation and benefits for individuals of all ages.

Multiple systematic reviews have determined that the primary supports and motivators for exercise engagement appear to be focused on two major areas: social engagement and general health benefits. Social motivators – such as being part of a group, meeting new people and reducing isolation – are top influencing factors for exercise participation in older adults, alongside the benefits of improved health and general well-being (enhanced mood, weight control, stress relief) (Franco et al., 2015; Spiteri et al., 2019). Less research has been conducted on the supports for exercise engagement among young adults, however, mood or motivational benefits (a sense of achievement, building confidence) and general health benefits (cardiovascular fitness, weight control) have been noted as primary motivators (Allender et al., 2006). In terms of the barriers for exercise participation, older adults often cite health concerns (comorbidities or pain/injury) as a strong factor in reducing the ability to partake in exercise, whereas both young and older adults mention environmental factors (access to transportation or facilities), lack of time available to exercise and decreased confidence as highly influential in hindering exercise participation (Allender et al., 2006; Franco et al., 2015; Spiteri et al., 2019).

To the best of the author's knowledge, no published study has focused on the supports and barriers specific to HIIE; however, the nature of a HIIE intervention appears to address many of the abovementioned factors. HIIE is well-known for its time-efficiency benefits, as it has been shown to induce similar or even superior physiological and health benefits (improved cardiovascular endurance, decrease body fat percentage) in a shorter timeframe when compared to traditional endurance protocols (Gibala et al., 2012; Tjønna et al., 2009). HIIE is also a safe and effective exercise protocol for both healthy and clinical populations, allowing for individuals from a range of health backgrounds and expertise to confidently partake in the exercise (Dun et al., 2019; Kirwan et al., 2017; Tjønna et al., 2009).

CHAPTER 3: CURRENT STUDY

3.1 Rationale

The influence of acute exercise on executive functions has become an increasingly popular research focus; however, little is still known about the specific factors that may mediate the effects of this relationship (Chang et al., 2012). Some research has suggested that exercise intensity can influence the magnitude and duration of post-exercise executive improvements, but a firm conclusion has yet to be made regarding high-intensity exercise due to the limited number of published studies, especially ones involving an interval training format as opposed to continuous exercise (Pontifex et al., 2019). Studies have suggested that high-intensity exercise may result in greater cognitive improvements if performed as intervals rather than continuous exercise, due to lower levels of physical and mental fatigue induced during an interval session (Gibala et al., 2012). Furthermore, the vast majority of high-intensity exercise studies have been performed solely with young adults, so it is unknown if improvements in executive functions are elicited similarly across age groups (Moreau & Chou, 2019). To date, there has been no published research that compares the effects of HIIE on executive functions among young and older adults.

This study compares the effects of an acute bout of HIIE on two areas of executive function – inhibition and working memory – among both young and older adults. Affective measurements were also examined to identify the potential influence of HIIE on affect. Although this study was stopped short of recruitment targets due to the 2019 novel coronavirus (COVID-19) pandemic, pilot results will help to inform future studies on the methodology and acceptability of a HIIE intervention across age groups, as well as inform future hypotheses related to age-specific improvements of executive functioning and affect following HIIE. Additional measures were included in the study to identify primary motivators and barriers for HIIE engagement, which may help to enhance health promotion strategies and increase participation in high-intensity exercise.

3.2 Thesis Objectives & Hypotheses

Objective 1. To compare changes in executive functions following a bout of HIIE and a control condition, as measured by the Stroop task (inhibitory control) and the n-back task (working memory).

Hypothesis 1.1. Relative to the pre-exercise timepoint, both young and older adults will show greater improvements in inhibitory control compared to working memory following HIIE compared to a control condition.

Hypothesis 1.2. Relative to the pre-exercise timepoint, executive functions will improve immediately following HIIE compared to a control condition and improvements will be maintained during the delay period.

Objective 2. To compare age-related performance changes in inhibitory control and working memory following HIIE.

Hypothesis 2. Relative to the control session, older adults will show a larger improvement in both inhibition and working memory scores immediately post-exercise and after the delay period compared to the improvement of young adults.

Objective 3. To compare participant's affective responses to HIIE across age groups.

Hypothesis 3. Relative to the control session, both young and older adults will show an increase in positive affect, exhaustion and tranquility scores following the exercise intervention.

Objective 4. To explore perceptions of, and barriers and motivators for, HIIE by age groups.

No specific hypothesis was determined relative to objective 4.

3.3 Methods

This experimental study compared the influence of exercise (versus stretching control) and age group (younger versus older adults) on inhibition and working memory. Cognitive assessments occurred immediately before the intervention (“pre-activity”), immediately following the intervention (“post-activity”) and after a 30-minute delay period (“delay”). All participants provided informed consent to participate in the study.

3.3.1 Participants

Healthy young adults (aged 18-30) and older adults (aged 60 and over) were recruited via posters at the University of Waterloo, the Waterloo Research in Aging Participant (WRAP) pool, a community presentation at the Waterloo Centre for Community, Clinical and Applied Research Excellence (CCCARE) and word of mouth. Participants were eligible to participate if they had no history of cardiovascular, musculoskeletal, neurological or cognitive issues. Participants must have also been considered safe for exercise to be eligible, as per the Get Active Questionnaire (GAQ) (Canadian Society for Exercise Physiology, 2017). Older adult participants were also required to have a score of 26 or above on the Montreal Cognitive Assessment (MoCA), as a score below 26 is indicative of possible cognitive impairment (Nasreddine et al., 2005). A description of the complete inclusion and exclusion criteria is outlined in table 3.1.

Table 3.1: Participant inclusion and exclusion criteria.

Criteria	Inclusion	Exclusion
Young adult (aged 18-30) OR older adult (aged 60+)	X	
MoCA Score $\geq$ 26 for older adults	X	
“No” to all medical screening form questions*	X	
“No” to all GAQ questions*	X	
Uncontrolled diabetes and/or hypertension **(not regulated by medicine, diet or exercise)**		X
History of heart disease or heart condition		X
History of neurological condition **(Stroke, Parkinsonism, recent concussion)**		X
Severe musculoskeletal issues / arthritis		X

* Or cleared by a physician to partake in high-intensity exercise.

3.3.2 Sample Size

A priori sample size targets were established to detect differences in cognitive outcomes between the exercise and control conditions, as well as between age groups. The effect size used to set sample size targets reflected an average across meta-analyses and most relevant studies (0.34) (Alves et al. 2012; Chang et al., 2012; Lambourne & Tomporowski, 2010). Using an alpha level of 0.05, power level of 0.8 and a repeated-measures within- and between-subjects design, a sample size of 20 participants per group was determined. When accounting for a 10% dropout rate, the required sample size was increased to 22 participants per group.

Unfortunately, due to immediate and long-term lab closures related to the COVID-19 outbreak in March 2020, the current study was unable to reach the projected sample size of 22 participants per group. Study enrolment was closed when 8 young adults and 7 older adult participants completed the study (those who were in progress were excluded). Consequently, the results should be considered preliminary and hypothesis-setting.

3.3.3 Study Design

Participants completed three sessions: a baseline session and two experimental sessions (exercise and control). The order of the two experimental sessions was randomized. Sessions were spaced approximately one week apart to avoid learning effects between sessions, with the order of the initial experimental session being counterbalanced across participants in each age group. To reduce the effects of age-related differences in circadian arousal levels, both age groups participated in their sessions during a time of day associated with higher cognitive alertness – the morning for older adults and the afternoon for young adults (Anderson et al., 2014; Schmidt et al., 2007). Older adult participants attended all sessions in the morning starting between 8:30am and 10:00am, whereas young adult participants attended all sessions in the afternoon beginning between 12:00pm and 1:30pm. Participants were asked to refrain from performing any moderate-to-high levels of physical activity 24 hours prior to each session. Cognitive tasks were performed at three separate timepoints during each experimental session, as detailed below.

Baseline Session

In the baseline session, participants were briefed on the requirements of the study and provided written informed consent. All participants then completed the general health questionnaire and GAQ to ensure that they were safe to perform high-intensity exercise. Following this, older adults performed the MoCA to screen for cognitive impairment. Participants then completed the Short Form Geriatric Depression Scale (GDS-15) to screen for depressive symptoms that would be considered as a potential moderator for outcome measures, if applicable (Guerin et al., 2018; Marc et al., 2008). Young adults completed the International Physical Activity Questionnaire (IPAQ) long-form, whereas older adults completed the Physical Activity Scale for the Elderly (PASE) to assess habitual physical activity levels (Craig et al., 2003; Washburn et al., 1999). Following the completion of all health and activity forms, resting blood pressure and heart rate was measured.

Participants then completed a round of 36 practice trials for each of the computerized Stroop conditions and 48 practice trials for each of the n-back conditions during the baseline session (tasks are detailed in section 3.3.4). Performance of the practice trials was to ensure that the instructions of the task were fully understood, as well as to reduce the potential of a learning effect during the experimental sessions.

The final component of the baseline session was a graded exercise test (GXT) to determine fitness level and target heart rate for the exercise intervention, based on HRR. The GXT protocol was a continuous, functional maximal exercise test on a recumbent bike that increased intensity (resistance) every two minutes until the participant was at a maximal fatigue state (American College of Sports Medicine, 2018; Beltz et al., 2016). Initial wattage was determined based on participant’s self-reported fitness levels and activity frequency (American College of Sports Medicine, 2018). An electrocardiogram (ECG) and blood pressure monitor was used throughout the GXT to monitor for adverse physiological changes that may have arisen in response to maximal exercise. HRR was determined by subtracting resting HR (as determined following the questionnaires) from the peak HR achieved during the GXT (American College of Sports Medicine, 2018).

Experimental Sessions

Study measures were consistent across both experimental sessions, with only the intervention differing between sessions (HIIE or a stretching control). Participants first had their resting heart rate and blood pressure taken. Following this, participants performed a practice block of both cognitive tasks: the computerized Stroop and n-back tasks (detailed below) (Redick & Lindsey, 2013; Stroop, 1935). Next, participants completed the PAAS prior to the pre-intervention cognitive tasks (Lox et al., 2000). Details of the PAAS and cognitive tasks can be found in section 3.3.4.

The first round of measured cognitive tasks were completed by participants directly before beginning their exercise or control intervention, at the pre-activity timepoint. The order of the tasks were consistent across sessions for each participant but were planned to be counterbalanced across participants. Due to the early completion of this study, 7 participants completed the exercise session first and 8 participants completed the control session first.

High Intensity Interval Exercise

In the exercise session, the HIIE intervention was performed on a recumbent bike and consisted of a 3-minute warm up at 50% HRR, 20 minutes of the HIIE protocol, and a 3-minute self-paced cool down. The HIIE protocol comprised of 1-minute cycling bouts at 80% HRR, interspersed by 1-minute low-intensity active rest periods at 40% HRR (Gibala et al., 2012). HR targets were set using the HRR calculated following the baseline session (80% or 40% * HRR + HRrest) (American College of Sports Medicine, 2018). Participants were required to maintain a cycling cadence of 60 rpm or above throughout the exercise session. Immediately prior to the completion of each high-intensity cycling bout, perceived exertion was measured using the 6 to 20-point Borg Rating of Perceived Exertion (RPE) scale (Borg, 1998). Blood pressure was taken every two minutes near completion of each HIIE bout, heart rate was noted every minute throughout the exercise intervention and ECG was continuously monitored.

Immediately following cool-down, participants engaged in the post-activity cognitive tasks followed by completion of the PAAS. Participants then read a book titled "*Spark: The Revolutionary New Science of Exercise and the Brain"* by John J. Ratey in a seated position until it had been 30 minutes since the cessation of exercise in order to prevent mental fatigue brought on by boredom. After 30 minutes, participants engaged in the final round of cognitive assessments.

Active Control

In the control condition, instead of the HIIE protocol, participants performed a 26-minute low-movement static stretching routine shown via video. The video was created by the researcher to provide low stimulation of physical and mental demands but still maintain interest to reduce boredom. Participants were instructed to follow the video routine without engaging in conversation in order to create a low-stimulus control environment (Pontifex et al., 2019). A Polar heartrate sensor and watch was worn during the control session to measure heartrate throughout the session.

3.3.4 Measures

Computerized Stroop Task

The Stroop task is a validated assessment of attentional control and inhibition, requiring participants to suppress conflicting information in order to perform the correct action (Aschenbrenner & Balota, 2015; Scarpina & Tagini, 2017; Stroop, 1935). The standard Stroop task is paper-administered; however, in this study, the Stroop task was modified to be performed on the computer using the Python extension, PsychoPy (Pierce et al., 2019). The computer-modified Stroop task is referred to as the computerized Stroop task.

The computerized Stroop task consisted of three conditions: congruent (each word printed in the corresponding color – either blue, red, or green), neutral (color words presented in white ink) and incongruent (each word printed in a non-matching color) (Aschenbrenner & Balota, 2015; Tsukamoto et al., 2012). In the congruent and neutral conditions, participants were instructed to indicate the word of the stimulus, whereas the incongruent condition required participants to indicate the ink color of the stimulus – thus creating a greater increase in attentional resources to supress the automatic response of reading the presented word (Dupuy et al., 2010; Stroop, 1935). Reponses were specified on the corresponding computer key. The computer keys “v” “b” and “n” corresponded to the red, blue and green colors, respectively, and were covered with a sticker that indicated the appropriate color (i.e., a red sticker covered the "v" key). Prior to beginning each task round, participants were given identical instructions to indicate the ink/name of the stimulus as quickly and accurately as possible.

During each Stroop condition, the stimulus was presented on-screen for a maximum of 2500ms, followed by an inter-trial interval that varied between 1000ms – 1500ms to avoid stimulus expectation (Langenecker et al., 2004). Responses that occurred after 2500ms and responses that indicated the incorrect color were counted as errors and not included in response time analysis. Participants first performed a practice block containing 36 trials of each Stroop condition (congruent, neutral, incongruent). A time period of approximately ten minutes separated the practice trials and the first performance trials (occurring at the pre-activity timepoint) to reduce carryover effects. During the performance trials, each condition comprised of 36 trials, equally distributed across the three colors (red, blue and green). The order of Stroop conditions remained consistent across participants and timepoints with the congruent condition performed first, neutral condition performed second and incongruent condition performed last.

Response time (ms) and percent error (% incorrect) were recorded as markers of inhibitory control, as well as to establish a Linear Integrated Speed-Accuracy Score (LISAS) (Lambourne & Tomporowski, 2010; Pontifex et al., 2019; Vandierendonck, 2018). The LISAS calculation uses both response time and percent error measures to establish an overall linear score that weights both measures similarly to account for speed-accuracy trade-offs during performance (Vandierendonck, 2017). As it is a speed-accuracy adjusted response time score, the LISAS score will be further referred to as RT_{LISAS}.

N-back Task

To assess working memory performance, the n-back task was used as the second cognitive test, comprising of the 0-back and 2-back conditions (Kirchner, 1958). Similar to the Stroop task, the n-back task was also programmed and performed on the computer using the Python extension, PsychoPy (Pierce et al., 2019). The n-back task requires participants to report whether or not the stimulus currently presented matches the stimulus that was seen *n* items previously, by pressing the corresponding computer key. The letter keys "r" and "i" corresponded to a "yes" and "no" response, respectively, and were covered by a sticker that said the word “yes” and “no”. Participants were instructed to respond as quickly and accurately as possible.

In the 0-back condition, participants were required to indicate if the current stimulus was identical to the letter previously indicated as the “target” letter at the start of the sequence, by pressing the appropriate key. In the 2-back condition, the participant would indicate if the stimulus was identical to the letter presented two trials previously (e.g., K-L-K), thus placing a stronger demand on working memory. The stimuli were randomly generated such that 33% of the letter stimuli were targets, with the remaining 67% being non-targets (Caciula et al., 2016; Hogan et al., 2013).

During each condition, a single random consonant was presented at an inter-stimulus interval of 3000ms. The stimulus then disappeared from the screen once a response had been initiated and was replaced with the next stimulus. Responses greater than 3000ms in length and incorrect responses were counted as errors and not included in response time analysis. Participants first completed two blocks of 24 practice trials for each of the 0-back and 2-back conditions. Practice trials and the first performance trials (at the pre-activity timepoint) were separated by approximately ten minutes to reduce carryover effects. Following the ten-minute period, participants completed the first round of performance trials. Performance trials consisted of two blocks of 24 trials for the 0-back and 2-back conditions each, with the order of the blocks alternating (0-back, 2-back, 0-back, 2-back). A ten-second break occurred following completion of each block to reduce mental fatigue. Similar to the Stroop task, response time and percent error were calculated with the primary objective of obtaining an RT_{LISAS} measure.

Physical Activity Affect Scale

The PAAS was used to evaluate affective states among participants (Lox et al., 2000). Affective states are thought to be highly influenced by exercise, thus leading to the development of the PAAS as a concise affect measurement tool (Bryan et al., 2007; Carpenter et al., 2010). The PAAS is a simple 12-item scale that requires participants to indicate how strongly they feel each affective state on a five-point scale (0 = do not feel to 4 = feel very strongly). The 12-item PAAS can then be categorized into four sub-scales: positive affect (upbeat, energetic, and enthusiastic), negative affect (miserable, discouraged, and crummy), physical exhaustion (tired, worn-out, and fatigued) and tranquility (calm, peaceful, and relaxed) (Lox et al, 2000). Participants completed the PAAS at the pre-activity and post-activity timepoints during the experimental sessions. The PAAS document can be found in appendix A.1.

Online Survey

All previous in-lab participants were contacted in September 2020 and invited to partake in a short quantitative survey using the online survey platform, Qualtrics (Qualtrics, Provo, UT). The online survey comprised of questions relating to exercise frequency and preference, experience of the in-lab HIIE intervention and perceived supports and barriers to engagement in HIIE (Hoare et al., 2017). The survey was open for two weeks, with participants being re-contacted through a follow-up invitation after the first week if they had not yet completed the survey. Participants were asked to rate a list of potential barriers and supports to engaging in HIIE on a scale from 1 (not at all limiting/supportive) to 4 (extremely limiting/supportive), e.g., “musculoskeletal concerns”, “time-efficiency benefits”. Additionally, participants indicated their frequency of exercise engagement and preference towards both HIIE and moderate-intensity continuous exercise (MICE), along with their in-lab experience of the HIIE intervention. The complete survey can be found in appendix A.2.

Additional Measures

Demographics

Demographic information including age, sex and years of education was recorded during the baseline session as part of the initial health screening questionnaire.

Physical Activity & Fitness Levels

The IPAQ long-form is a widely-used physical activity questionnaire that measures weekly high, moderate and light physical activity levels to obtain a score of overall MET-minutes/week (Craig et al., 2003; Lee et al., 2011). Similarly, the PASE is a tool used to measure physical activity levels in older adults, by recording the duration, frequency, intensity and type of physical activity undertaken over a seven day period (Washburn et al., 1999). While well validated among young adults, the IPAQ has shown only slight validity among older adults, whereas the PASE provides a more accurate and validated reflection of older adult's physical activity behaviours (Cleland et al., 2018; Tomioka et al., 2011; Washburn et al., 1999). Therefore, young adults completed the IPAQ and older adults completed the PASE during the baseline session to assess habitual physical activity levels. Physical activity levels were then mapped to fitness levels using the designated PASE and IPAQ classifications, which incorporate the METS of each activity, along with activity frequency and duration (American College of Sports Medicine, 2018; Craig et al., 2003; Washburn et al., 1999; Forde, 2018). The IPAQ and PASE questionnaires can be found in appendix A.3 and A.4, respectively.

The outcome of the GXT allowed for the fitness level of participants to be calculated using the VO_2 maximum metabolic equation for cycling:

$(VO_2 \text{ max} = (1.8\ (6.1 \text{ x watts}_{final}) / \text{kg}) + 7)$

Where watts_{final} is the final wattage reached by the participant during the GXT and kg is the participant's weight in kilograms (American College of Sports Medicine, 2018).

Screening Measures

Finally, two measures were collected for screening purposes during the baseline session, the MoCA and the GDS-15. The MoCA is a cognitive assessment tool designed to screen for mild cognitive impairment in older adults by testing performance in various domains, including executive functioning, memory, attention and language comprehension (Nasreddine et al., 2005). The GDS-15 is an instrument used to identify depressive symptoms in older adults, although it has also been validated for use in the young adult population (Guerin et al., 2018; Marc et al., 2008; Yesavage & Sheikh, 1986). The GDS-15 asks respondents to respond "yes" or "no" in reference to how they have felt within the past week when presented with specific examples. Scores are then calculated to obtain an overall classification, ranging from "normal" to "severe depression". Both young and older adults completed the GDS-15, whereas the MoCA was only administered to older adults.

3.3.5 Statistical Analysis

All statistical analyses were performed in RStudio version 1.3.1093. Data from the Stroop (congruent, neutral and incongruent) and n-back (0-back, 2-back) tasks were assessed for normality through Q-Q plots, the Shapiro-Wilk test and histograms. Homogeneity of variance was also tested using Mauchly's sphericity test. Deviations from a normal distribution were identified in all cognitive task datasets, resulting in the application of log transformations to the raw skewed data to transform the data into a normal distribution. There were no violations to the Mauchly's test of sphericity within the log transformed data.

Participant and exercise characteristics were described as mean and standard deviation (SD) or percent and number (n) and compared between young and older adults using an unpaired Student's *t* test to identify significant differences.

Incorrect trials of the Stroop and n-back tasks were excluded from analysis, along with trials of response times (RT) that were very fast (less than 200ms), very slow (more than 3000ms), or more than 3 SD from the age group mean. Two participants - one in the older adult group and one in the young adult group - were removed from the 2-back analysis, as their average scores were more than 3 SD above the age group mean. Additionally, one young adult did not complete the Stroop task due to colorblindness. Following the data removal, there were complete datasets from 7 older adults and 7 young adults for all conditions of the Stroop task, 6 older adults and 7 young adults for the 2-back task and 7 older adults and 8 young adults for the 0-back task.

In order to account for speed-accuracy trade-offs, RT_{LISAS} was used as the primary outcome variable for analysis (Vandierendonck, 2017; Vandierendonck, 2018). RT_{LISAS} is calculated as:

$$RT_{LISAS} = RT + \left(\frac{sd\ RT}{sd\ PE} \times PE\right)$$

Where RT and PE are the participant's mean response time and proportion error (1 – accuracy) for each set of scores, by condition and time, separated by congruency. $sdRT_{RT}$ refers to the overall standard deviation of all correct RTs, and sdPE to the overall standard deviation of PE. If PE was zero (at 100% accuracy), the latter portion of the equation was then set to zero, resulting in the RT_{LISAS} score equating to the RT score.

Responses from the Physical Activity Affect Scale (PAAS) were classified into one of the four affective sub-scales: positive affect, negative affect, physical exhaustion and tranquility (Lox et al, 2000). Scores within each sub-scale were then treated as independent outcomes to identify changes in affective states from pre- to post-intervention across conditions and differences between age groups.

Outcome data – being RT_{LISAS} scores or PAAS scores – were analyzed separately using a mixed measures, factorial ANOVA. For the cognitive tasks (with RT_{LISAS} as the outcome measure) the ANOVA included two between-subjects factors (age group: young adult, older adult; session order: exercise-first, control-first) and two within-subjects factors (condition: exercise, control; timepoint: pre-activity, post-activity, delay). Session order was included in the analysis plan to control for changes from session 1 to session 2 due to practice effects. For the PAAS (with the scores as the outcome measure) the ANOVA included one between-subjects factor (age group: young adult, older adult) and two within-subjects factors (condition: exercise, control; timepoint: pre-activity, post-activity). Main effects and interactions were included. Estimates of effects were calculated using generalized eta-squared (η2G). Post hoc analyses of main effects were completed using Tukey's test and pairwise comparisons were used to identify significant interactions.

Z-scores were also calculated to standardize and compare group-specific changes across cognitive tasks. Only Z-scores for the incongruent and 2-back tasks were calculated, as these were the two strongest measures of inhibition and working memory, respectively. Z-scores were calculated using the RT_{LISAS} output for all timepoints, conditions, and participants as the raw scores. Z-scores were then analyzed using a mixed measures factorial ANOVA, with one between-subjects factor (session order: exercise-first, control-first) and three within-subjects factors (condition: exercise, control; timepoint: pre-activity, post-activity, delay; cognitive task: incongruent, 2-back). Similar to the RT_{LISAS} ANOVA, session order was included in the analysis to control for changes from session 1 to session 2 due to practice effects. To satisfy the goal of identifying group-specific changes, older adult and young adult Z-scores were calculated separately for both the incongruent and 2-back tasks. It should be noted that due to missing values from participants (e.g., those that could not complete the incongruent task, or 2-back outlier data previously removed), the number of participants included in the Z-score analysis was low (6 young adults and 6 older adults). For all outcome analyses, the significance level was set at *p* = 0.05. However, given the limited sample size, p-values that were <0.2 were followed up with post hoc testing for the purpose of future hypothesis setting.

Participant responses on the online survey were coded on a scale ranging from 1 (not at all) to 4 (extremely), with the exception of enjoyment of the HIIE session coded on a scale ranging from 1 (strongly disliked) to 5 (strongly enjoyed).

3.4 Results

Participant Characteristics

Eight young adults (mean age ± SD = 21.5 ± 2.3; female = 5) and seven older adults (mean age ± SD = 73.0 ± 4.7; female = 6) completed the study. This sample size was significantly less than the target size of 22 participants in each age group due to COVID-19 lab closures. On average, young adult participants were moderately-to-highly active and had an estimated VO_2 max score (a measure of cardiorespiratory fitness) that placed them in the “fair” fitness category (American College of Sports Medicine, 2018; Craig et al., 2013). Older adult participants were moderately active, with an average estimated VO_2 max score within the “excellent” fitness category (American College of Sports Medicine, 2018; Washburn et al., 1999). Participant characteristics are summarized in table 3.2.

Table 3.2: Participant characteristics, presented as mean ± SD or % (n).

Participant Characteristic	**Young Adult (n=8)**	**Older Adult (n=7)**
Age *(years)*	21.5 ± 2.3	73.0 ± 4.7
Female *% (n)*	62.5% (5)	85.7% (6)
Education *(years)*	16.3 ± 2.0	16.0 ± 2.1
Medical conditions % (*n)*	0%	25% (2)**
BMI *(kg/m^2)* ($p = 0.058$)	21.9 ± 2.1	24.5 ± 2.9
PASE Score	--	108.9 ± 42.7
IPAQ Score *(MET-min/week)*	2050.4 ± 1468.2	--
Estimated VO2 max *(mLO2/kg/min)* ($p = 0.008$)*	35.5 ± 7.2	25.0 ± 5.7

BMI = Body Mass Index; PASE = Physical Activity Scale for the Elderly; IPAQ = International Physical Activity Questionnaire; VO_2 max = maximum rate of ventilatory oxygen consumption.
*Significant difference between groups.
**Two participants had hypertension – no other conditions identified among participants.

Exercise Characteristics

Characteristics from the exercise and control session interventions are outlined in table 3.3. Young and older adult participants completed the HIIE intervention at an average of 81% and 84% of their HRR, respectively ($p = 0.488$). Both groups indicated their final RPE to be 15 points on the 6-20 scale ($p = 0.396$), corresponding to a “hard” level of exertion (Borg, 1998). During the control condition, young and older adult participants completed the low-intensity stretching activity at an average of 16% and 11% of their HRR ($p = 0.011$).

Table 3.3: Exercise characteristics, including heart rate (HR) beats/min, percent of heart rate reserve (HRR) and rate of perceived exertion (RPE) score.

Exercise Characteristics	**Young Adult (Mean ± SD)**	**Older Adult (Mean ± SD)**
Resting HR	65 ± 6	69 ± 4
Final Exercise HR ($p = 0.001$)*	155 ± 11	126 ± 16
Final HR as %HRR	81%	84%
Final Exercise RPE	15.0 ± 0.7	15.0 ± 0.5
Final Control HR	89 ± 11	83 ± 4
Final HR as %HRR ($p = 0.011$)*	16%	11%

*Significant difference between groups.

Cognitive Results

3.4.1 Stroop Task

A summary table of group RT_{LISAS} results from the congruent, neutral and incongruent tasks by condition and age group is shown in table 3.4.

Table 3.4: Group RT_{LISAS} scores (estimated marginal means ± standard error) for the Stroop tasks across all conditions, timepoints and age groups.

Condition	**Exercise Session**			**Control Session**		
	Pre-activity	**Post-activity**	**Delay**	**Pre-activity**	**Post-activity**	**Delay**
Young Adults						
Congruent	484 ± 19.3	462 ± 24.2	483 ± 23.0	516 ± 46.0	477 ± 15.6	465 ± 9.1
Neutral	531 ± 25.0	494 ± 20.5	512 ± 19.6	524 ± 28.1	502 ± 14.0	505 ± 12.8
Incongruent	590 ± 18.9	583 ± 22.6	548 ± 25.7	586 ± 32.4	586 ± 29.6	595 ± 29.6
Older Adults						
Congruent	653 ± 20.1	603 ± 19.8	638 ± 24.7	632 ± 22.6	613 ± 20.2	609 ± 14.8
Neutral	667 ± 20.9	632 ± 22.6	650 ± 24.6	646 ± 31.3	659 ± 25.1	639 ± 25.3
Incongruent	912 ± 53.1	851 ± 38.1	866 ± 46.0	951 ± 79.1	891 ± 50.1	877 ± 49.0

Congruent

There was a main effect of age group for congruent RT_{LISAS} scores, where older adults demonstrated higher RT_{LISAS} scores compared to young adults ($F_{(1,10)} = 29.15$, $p = 0.0003$, $\eta^2_G = 0.69$; $M_{older} = 625$ vs $M_{young} = 481$). A main effect of timepoint was also identified ($F_{(2,20)} = 9.11$, $p = 0.002$, $\eta^2_G = 0.06$), where post hoc tests revealed a significant improvement from pre-activity to post-activity ($M_{pre} = 571$ vs $M_{post} = 539$, $p = 0.001$) and from pre-activity to the delay period ($M_{pre} = 571$ vs $M_{delay} = 549$, $p = 0.028$); however no significance was found from the post-activity to the delay period ($M_{post} = 539$ vs $M_{delay} = 549$, $p = 0.371$). The age group by condition interaction showed a trend towards significance ($F_{(1,10)} = 3.00$, $p = 0.114$, $\eta^2_G = 0.01$), with young adults performing significantly better in both the exercise and control conditions compared to older adults (exercise: $M_{young} = 476$ vs $M_{older} = 632$, $p = 0.001$; control: $M_{young} = 486$ vs $M_{older} = 618$, $p = 0.003$). No other effects neared significance (p>0.20). The primary interactions of interest, condition by timepoint ($F_{(2,20)} = 1.73$, $p = 0.27$, $\eta^2_G = 0.02$) and age group by condition by timepoint ($F_{(2,20)} = 0.65$, $p = 0.53$, $\eta^2_G = 0.01$) did not near significance.

Neutral

There was a main effect of age group ($F_{(1, 10)} = 21.12$, $p = 0.001$, $\eta^2_G = 0.63$) for neutral RT_{LISAS} scores, where older adults demonstrated higher scores compared to young adults ($M_{older} = 649$ vs $M_{young} = 511$). A main effect of timepoint was also identified ($F_{(2, 20)} = 5.05$, $p = 0.017$, $\eta^2_G = 0.03$), where post hoc analysis indicated an improvement from pre-activity to post-activity ($M_{pre} = 592$ vs $M_{post} = 572$, $p = 0.015$) and a trend towards significance from pre-activity to the delay period ($M_{pre} = 592$ vs $M_{delay} = 577$, $p = 0.093$). There was no significant difference from post-activity to the delay period ($M_{post} = 572$ vs $M_{delay} = 577$, $p = 0.665$). The condition by timepoint interaction also showed a trend towards significance ($F_{(2, 20)} = 2.27$, $p = 0.129$, $\eta^2_G = 0.02$). Post hoc tests were done to explore this effect despite the p-value, identifying a change in RT_{LISAS} scores from pre-activity to post-activity in the exercise condition ($M_{pre} = 599$ vs $M_{post} = 563$, $p = 0.013$) but not among any other timepoints in the exercise condition ($p>0.48$) or in the control condition ($p>0.87$). All other comparisons were non-significant and did not indicate trends towards significance ($p>0.30$). The other primary interaction of interest, age group by condition by timepoint, showed a non-significant interaction ($F_{(2, 20)} = 0.35$, $p = 0.708$).

Incongruent

Similar to the congruent and neutral results, RT_{LISAS} analysis for the incongruent task also showed a main effect of age group, with older adults revealing higher RT_{LISAS} scores than young adults ($F_{(1, 10)} = 92.60$, $p < 0.0001$, $\eta^2_G = 0.86$; $M_{older} = 891$ vs $M_{young} = 581$). The main effect of timepoint showed a trend towards significance ($F_{(2, 20)} = 3.21$, $p = 0.062$, $\eta^2_G = 0.05$) where post hoc analysis indicated an improvement in RT_{LISAS} scores from pre-activity to the delay period ($M_{pre}= 760$ vs $M_{delay} = 721$, $p = 0.059$) and a slight trend towards improvement from pre-activity to post-activity, but this did not near significance ($M_{pre}= 760$ vs $M_{post} = 728$, $p = 0.202$). The main effect of condition also demonstrated a trend towards significance ($F_{(1, 10)} = 2.57$, $p = 0.140$, $\eta^2_G = 0.02$), with post hoc tests identifying a trend towards higher RT_{LISAS} scores during the control condition compared to the exercise condition ($M_{control} = 748$ vs $M_{exercise} = 725$, $p = 0.140$). Finally, a trend towards significance was identified within the age group by condition by timepoint interaction ($F_{(2, 20)} = 2.71$, $p = 0.091$, $\eta^2_G = 0.02$). Post hoc tests found that young adults performed better across all conditions and timepoints compared to older adults (*p*<0.001). In addition, while young adults showed non-significant changes across conditions (*p*>0.90), older adults demonstrated lower p-values for trends in RTLISAS scores, but still far from significant (*p*>0.27). All other comparisons were non-significant and did not indicate trends towards significance (*p*>0.30). Individual and group RTLISAS scores for the incongruent task are also highlighted in figure 3.1.

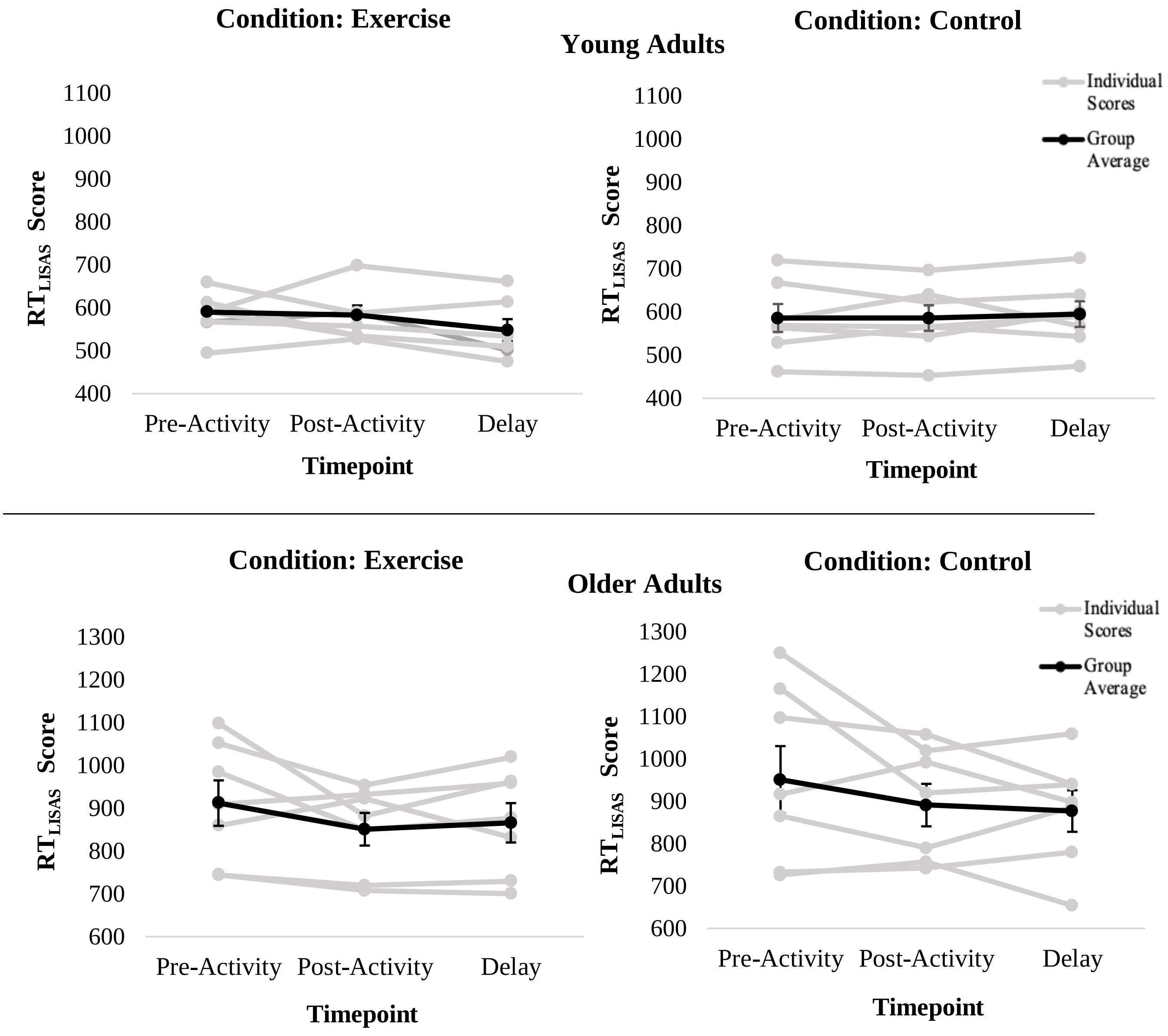

Figure 3.1: Incongruent Stroop task RTLISAS scores for young adult (top row) and older adult participants (bottom row). Average group RTLISAS score (mean ± SD bars) is shown in black.

3.4.2 N-back Task

A summary table of group RT_{LISAS} results from the 0-back and 2-back tasks is shown in table 3.5.

Table 3.5: Group RT_{LISAS} scores (estimated marginal means ± standard error) for the n-back tasks across all conditions, timepoints and age groups.

Condition	**Exercise Session**			**Control Session**		
	Pre-activity	**Post-activity**	**Delay**	**Pre-activity**	**Post-activity**	**Delay**
Young Adults						
0-back	448 ± 18.2	409 ± 19.8	424 ± 19.2	443 ± 34.3	443 ± 24.1	424 ± 25.5
2-back	823 ± 105.4	609 ± 48.7	577 ± 38.0	716 ± 92.8	631 ± 68.1	624 ± 65.8
Older Adults						
0-back	586 ± 27.7	581 ± 33.8	540 ± 32.3	571 ± 41.2	555 ± 35.7	581 ± 35.4
2-back	983 ± 107.9	938 ± 99.0	940 ± 118.2	994 ± 128.5	1014 ± 130.0	966 ± 116.6

Zero-back (0-back)

Analysis for the RT_{LISAS} scores for the 0-back task showed a main effect of age group ($F_{(1, 11)} = 17.73$, $p = 0.001$, $\eta^2_G = 0.58$) indicating a significant age difference among participant groups where older adults demonstrated higher RT_{LISAS} scores than young adults ($M_{older} = 569$ vs $M_{young} = 432$). A main effect of timepoint on RT_{LISAS} scores was also found ($F_{(2, 22)} = 3.86$, $p = 0.036$ $\eta^2_G = 0.02$). Post hoc tests revealed a significant improvement from pre-activity to the delay period ($M_{pre} = 512$ vs $M_{delay} = 492$, $p = 0.038$), with a trend towards improvement from pre-activity to post-activity ($M_{pre} = 512$ vs $M_{post} = 497$, $p = 0.123$) but no effect from post-activity to the delay period ($M_{post} = 497$ vs $M_{delay} = 492$, $p = 0.826$). A significant age group by condition by timepoint interaction was also found ($F_{(2, 22)} = 7.09$, $p = 0.005$, $\eta^2_G = 0.03$). Post hoc tests discovered a trend towards significance, where young adults consistently performed better compared to older adults across all conditions and timepoints ($p<0.20$). Additionally, post hoc tests found that, during the exercise condition, young adults significantly improved from pre-activity to post-activity ($M_{pre} = 448$ vs $M_{post} = 409$, $p = 0.06$) and older adults showed a trend towards improvement from pre-activity to the delay period ($M_{pre} = 586$ vs $M_{delay} = 540$, $p = 0.169$). Similarly, a trend towards significance within the timepoint by condition interaction was also identified ($F_{(2, 22)} = 2.79$, $p = 0.083$, $\eta^2_G = 0.01$). Post hoc analysis revealed an improvement in RT_{LISAS} scores from pre-activity to the delay period in the exercise condition ($M_{pre} = 517$ vs $M_{delay} = 482$, $p = 0.013$) but not the control condition ($M_{pre} = 507$ vs $M_{delay} = 502$, $p = 0.998$), as well as a trend towards significance from pre-activity to post-activity in the exercise condition ($M_{pre} = 517$ vs $M_{post} = 495$, $p = 0.118$), but not in the control condition ($M_{pre} = 507$ vs $M_{post} = 499$, $p = 0.998$). All other comparisons were non-significant and did not indicate trends towards significance ($p > 0.30$).

Two-back (2-back)

There was a main effect of age group for 2-back RT_{LISAS} scores ($F_{(1, 9)} = 10.95$, $p = 0.009$, $\eta^2_G = 0.50$), once again representing a significant age difference among groups with older adults demonstrating higher RT_{LISAS} scores than young adults ($M_{older} = 973$ vs $M_{young} = 663$, $p = 0.009$). There was also a main effect of timepoint ($F_{(2, 18)} = 10.54$, $p = 0.001$, $\eta^2_G = 0.74$), where post hoc analysis indicated a significant improvement from pre-activity to post-activity ($M_{pre} = 879$ vs $M_{post} = 798$, $p = 0.0084$) and from pre-activity to the delay period ($M_{pre} = 879$ vs $M_{delay} = 777$, $p = 0.0004$) but not from post-activity to the delay period ($M_{post} = 798$ vs $M_{delay} = 777$ $p = 0.609$). An age group by timepoint interaction was also identified ($F_{(2, 18)} = 6.36$, $p = 0.008$, $\eta^2_G = 0.05$). Post hoc tests revealed that the young adult participant group improved from pre-activity to post-activity ($M_{pre} = 770$ vs $M_{post} = 620$, $p = 0.002$) as well as from pre-activity to the delay period ($M_{pre} = 770$ vs $M_{delay} = 601$, $p = 0.0004$), whereas the older adult group did not exhibit significant changes across timepoints ($p > 0.90$).

A significant timepoint by condition interaction was identified ($F_{(1, 9)} = 4.69$, $p = 0.023$, $\eta^2_G = 0.02$). Post hoc analysis revealed that RT_{LISAS} scores improved during the exercise condition from pre-activity to post activity ($M_{pre} = 903$ vs $M_{post} = 774$, $p = 0.002$) and from pre-activity to the delay period ($M_{pre} = 903$ vs $M_{delay} = 759$, $p = 0.0002$), whereas no significant changes were identified across timepoints in the control condition ($p > 0.36$). Similarly, a trend towards significance was identified among the age group by timepoint by condition interaction ($F_{(2, 18)} = 1.81$, $p = 0.192$, $\eta^2_G = 0.01$), where post hoc analysis identified a significant improvement in RT_{LISAS} scores among the young adult group during the exercise condition, from pre-activity to post-activity ($M_{pre} = 823$ vs $M_{post} = 609$, $p = 0.0003$) and from pre-activity to the delay period ($M_{pre} = 823$ vs $M_{delay} = 577$, $p < 0.0001$), although no effect was seen from post-exercise to delay among this group ($M_{post} = 609$ vs $M_{delay} = 577$, $p = 0.997$). No significant effects were observed in the older adult group across any timepoint and condition interactions ($p > 0.90$). Individual and group RT_{LISAS} scores for the 2-back task are also highlighted in figure 3.2.

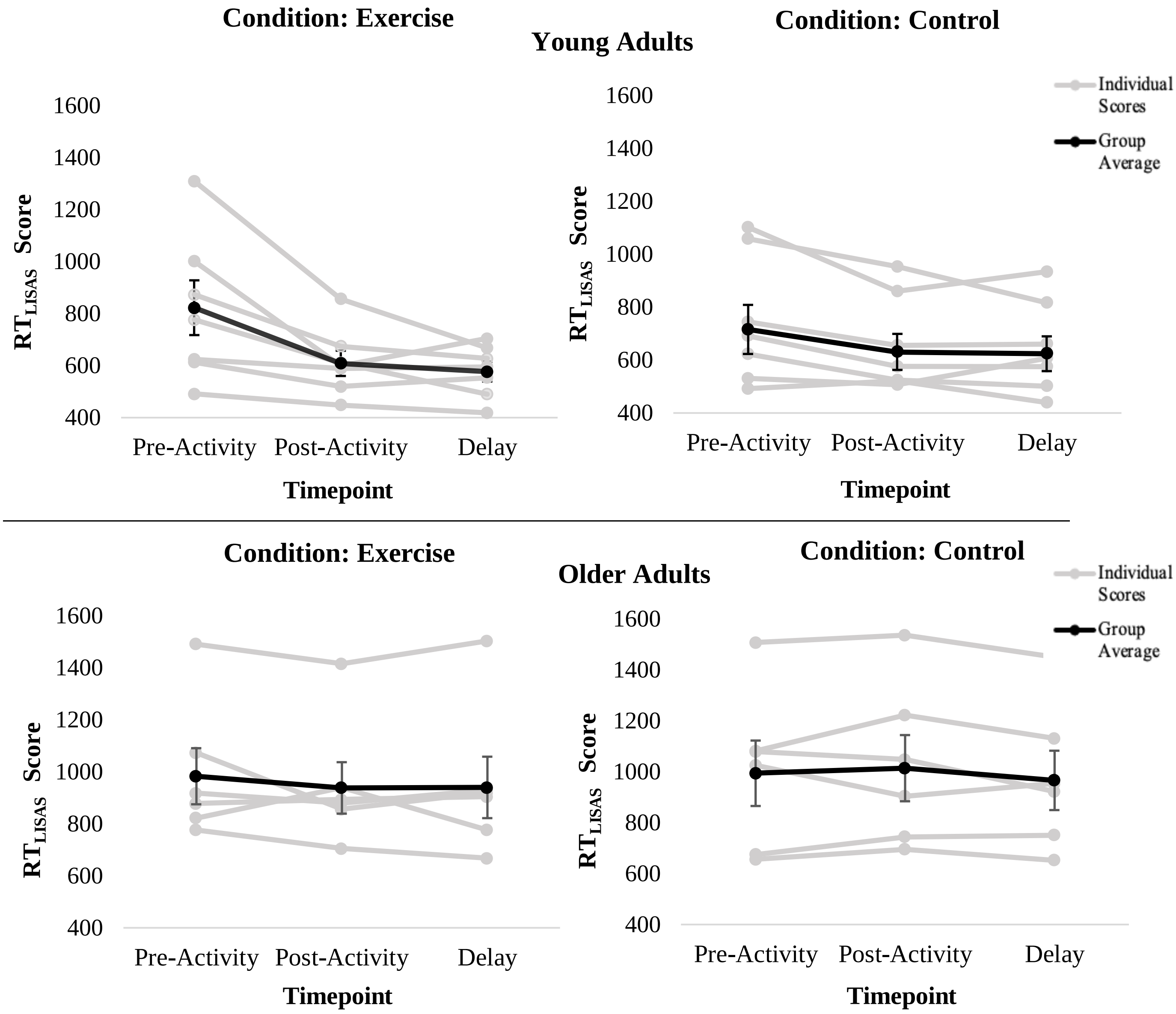

Figure 3.2: 2-back n-back task individual RT_{LISAS} scores for young adult (top row) and older adult participants (bottom row). Average group score (mean ± SD bars) is shown in black.

3.4.3 Z-scores

Table 3.6 summarizes the group Z-scores (mean ± SD) for both the incongruent and the 2-back tasks across all conditions, timepoints and age groups. Figure 3.3 illustrates the task-specific changes in group Z-scores across all conditions, timepoints and age groups.

Young Adults

There was a significant main effect of timepoint ($F_{(2, 8)} = 6.09$, $p = 0.025$, $\eta^2_G = 0.09$), with post hoc tests revealing a larger change in Z-scores from pre-activity to the delay period ($M_{pre} = 0.320$ vs $M_{delay} = -0.265$, $p = 0.021$), as well as a trend towards significance from pre-activity to post-activity ($M_{pre} = 0.320$ vs $M_{post} = -0.055$, $p = 0.129$), but not from post-activity to the delay period ($M_{post} = -0.055$ vs $M_{delay} = -0.265$, $p = 0.467$). There was a trend towards significance within the timepoint by cognitive task interaction ($F_{(2, 8)} = 3.56$, $p = 0.078$, $\eta^2_G = 0.04$), with post hoc tests revealing a significant change in Z-scores during the 2-back task, from pre-activity to the delay period ($M_{pre} = 0.628$ vs $M_{delay} = -0.287$, $p = 0.008$) as well as a trend towards a significant change from pre-activity to post-activity ($M_{pre} = 0.628$ vs $M_{post} = -0.058$, $p = 0.062$) but no significance from post-activity to the delay period ($M_{post} = -0.058$ vs $M_{delay} = -0.287$, $p = 0.896$) or during any of the incongruent timepoints ($p>0.8$). Finally, a trend towards significance was identified within the timepoint by condition interaction ($F_{(2, 8)} = 3.00$, $p = 0.107$, $\eta^2_G = 0.03$) where post hoc analysis found a significant change in Z-scores during the exercise condition from pre-activity to the delay period ($M_{pre} = 0.475$ vs $M_{delay} = -0.437$, $p = 0.008$) and a trend towards significance from pre-activity to post-activity ($M_{pre} = 0.475$ vs $M_{post} = -0.097$, $p = 0.146$) but no significance from post-activity to the delay period ($M_{post} = -0.097$ vs $M_{delay} = -0.437$, $p = 0.896$) or within any of the timepoints during the control condition ($p>0.83$).

Older Adults

The main effect of timepoint showed a trend towards significance ($F_{(1, 4)} = 2.18$, $p = 0.175$, $\eta^2_G = 0.04$); however, there was little difference in post hoc analysis from pre-activity to post-activity ($M_{pre} = 0.189$ vs $M_{post} = -0.102$, $p = 0.213$) or from pre-activity to the delay period ($M_{pre} = 0.189$ vs $M_{delay} = -0.087$, $p = 0.243$). There was also a trend towards significance in the timepoint by cognitive task interaction ($F_{(2, 8)} = 4.25$, $p = 0.055$, $\eta^2_G = 0.02$), where post hoc tests found a trend towards improvement from the pre-activity to post activity timepoint in the incongruent task ($M_{pre} = 0.320$ vs $M_{post} = -0.218$, $p = 0.088$), and a very slight trend towards improvement from the pre-activity to delay period timepoint in the incongruent task ($M_{pre} = 0.320$ vs $M_{delay} = -0.102$, $p = 0.241$) but not among the post-activity to delay timepoint ($M_{post} = -0.218$ vs $M_{delay} = -0.102$, $p = 0.985$) or in the 2-back task ($p>0.97$). There were no other trends towards significance among any other combinations ($p>0.30$).

Table 3.6: Group Z-scores (mean ± SD) for the incongruent Stroop task and 2-back n-back task across all conditions, timepoints and age groups.

Young Adults

Condition	**Exercise Session**			**Control Session**		
	Pre-activity	Post-activity	Delay	Pre-activity	Post-activity	Delay
Incongruent	0.09 ± 0.73	-0.02 ± 0.87	-0.49 ± 0.99	0.11 ± 1.25	0.10 ± 1.14	0.21 ± 1.14
2-back	0.68 ± 1.40	-0.31 ± 0.65	-0.49 ± 0.50	0.36 ± 1.22	-0.10 ± 0.90	-0.15 ± 0.87

Older Adults

Condition	**Exercise Session**			**Control Session**		
	Pre-activity	Post-activity	Delay	Pre-activity	Post-activity	Delay
Incongruent	0.12 ± 1.01	-0.31 ± 0.72	-0.20 ± 0.87	0.50 ± 1.15	0.01 ± 0.95	-0.12 ± 0.93
2-back	0.04 ± 0.99	-0.13 ± 0.91	-0.12 ± 1.08	0.08 ± 1.18	0.16 ± 1.19	-0.02 ± 1.07

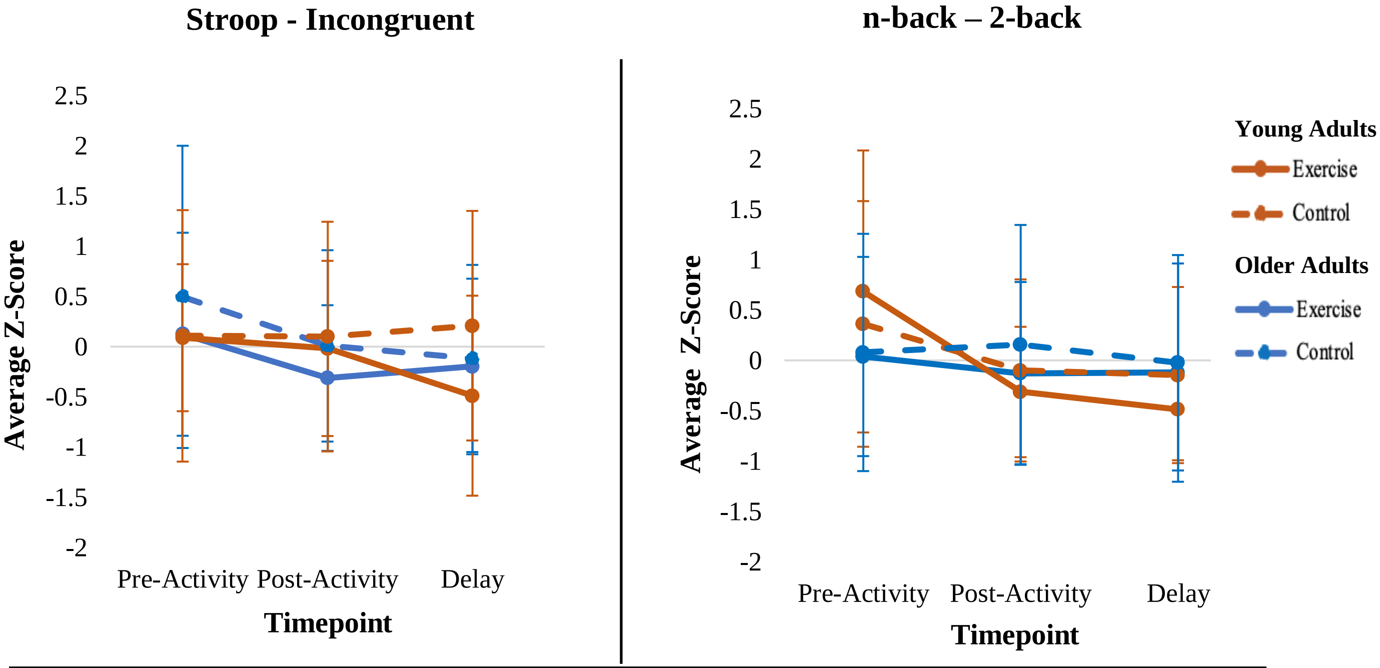

Figure 3.3: Group Z-scores (mean ± SD) for the Incongruent Stroop task (left) and 2-back n-back task (right) across all conditions, timepoints and age groups.

3.4.4 Physical Activity Affect Scale

All participants completed the PAAS questionnaire prior to and following the study interventions (HIIE, stretching control). Figure 3.4 illustrates the changes in PAAS scores.

Positive Affect

Analysis identified a trend towards significance within the main effect of age group ($F_{(1, 13)} = 1.57$, $p = 0.223$, $\eta^2_G = 0.01$), where older adults exhibited greater positive affect compared to young adults ($M_{older} = 2.30$ vs $M_{young} = 1.92$). A trend towards significance was also observed within the age group by condition interaction ($F_{(1, 13)} = 3.02$, $p = 0.106$, $\eta^2_G = 0.03$), but post hoc analysis did not find any significant effects between combinations (p>0.30). Similarly, a trend towards significance was also identified in the timepoint by condition interaction ($F_{(1, 13)} = 2.91$, $p = 0.112$, $\eta^2_G = 0.02$). Post hoc analysis did not identify any significant effects between timepoint by condition combinations (p>0.30) All other comparisons were non-significant and did not indicate trends towards significance (p>0.30).

Negative Affect

A trend towards significance was noted in the age group by condition interaction ($F_{(1, 13)} = 2.01$, $p = 0.179$, $\eta^2_G = 0.02$), however, post hoc analysis did not identify any trends within this interaction ($p>0.60$). All other comparisons were non-significant and did not indicate trends towards significance ($p>0.30$).

Physical Exhaustion

There was a main effect of age group for physical exhaustion scores ($F_{(1, 13)} = 4.83$, $p = 0.046$, $\eta^2_G = 0.13$), with post hoc analysis revealing significantly greater overall scores of physical exhaustion among young adults compared to older adults ($M_{young} = 1.05$ vs $M_{older} = 0.40$). There was also a trend towards significance in the age group by timepoint interaction ($F_{(1, 13)} = 2.42$, $p = 0.144$, $\eta^2_G = 0.01$), where post hoc analysis identified higher exhaustion pre-activity among young adults versus older adults ($M_{young} = 1.19$ vs $M_{older} = 0.379$, $p = 0.083$) but not post-activity scores ($M_{young} = 0.918$ vs $M_{older} = 0.426$, $p = 0.423$). All other comparisons were non-significant and did not indicate trends towards significance ($p>0.30$).

Tranquility

A slight trend towards significance was identified within the main effect of condition ($F_{(1, 13)} = 1.86$, $p = 0.195$, $\eta^2_G = 0.02$), where post hoc analysis revealed greater tranquility scores during the exercise condition compared to the control condition ($M_{exercise} = 2.08$ vs $M_{control} = 1.86$ $p = 0.195$). Similarly, a trend towards significance was identified in the age group by condition interaction ($F_{(1, 13)} = 3.79$, $p = 0.074$, $\eta^2_G = 0.03$), with post hoc analyses revealing a trend towards higher tranquility in the exercise condition among young adults ($M_{exercise} = 2.27$ vs $M_{control} = 1.73$, $p = 0.121$) but not older adults ($M_{exercise} = 1.88$ vs $M_{control} = 1.98$, $p = 0.978$). No other comparisons neared significance ($p>0.50$).

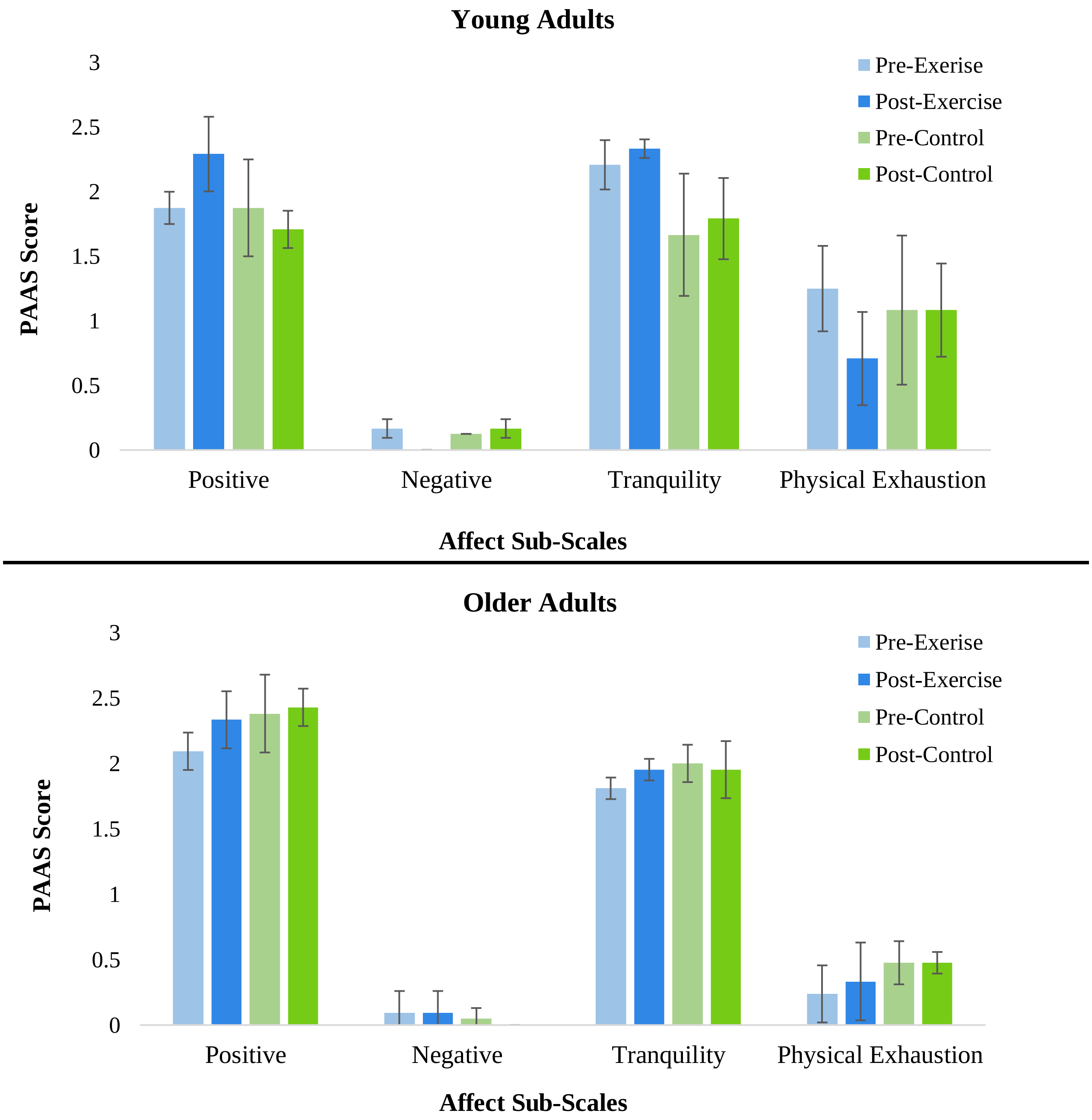

Figure 3.4: Group change (mean ± SD) in affect sub-scales from pre- to post-intervention by condition.

3.4.5 Online Survey

A total of six young adults (mean age ± SD = 21.5 ± 2.6; female = 5) and five older adults (mean age ± SD = 73.6 ± 5.5; female = 6) completed the survey, with a response rate of 73.3% overall. Table 3.7 highlights the results of the survey.

Prior to the in-lab session, one young adult and four older adult participants had never engaged in HIIE. In comparison, all participants indicated that they had engaged in MICE previously, with an average MICE frequency of 1-2 times per week. The average frequency of HIIE engagement for participants who had performed HIIE prior to the in-lab session was 1-2 times per week. The mean enjoyment rating of the HIIE session for older and young adults was 4.2 and 4.3 out of a 5-point scale, respectively, which correlates to a "high" level of enjoyment.

Musculoskeletal benefits was the top rated factor for influencing participation in HIIE among both age groups, with a mean score of 4.0 for young adults (maximum (max): 4.0, minimum (min): 3.0) and 3.8 for older adults (max: 4.0, min: 3.0) out of a 4-point scale. Cardiovascular benefits (rated 3.5 (max: 4.0, min: 2.0) and 3.6 (max: 4.0, min: 3.0), respectively) and motivational / mood benefits (rated 3.2 (max: 4.0, min: 2.0) and 3.4 (max: 4.0, min: 3.0), respectively) were also highly ranked and similar among young and older adults. Time-efficiency benefits were rated as being more important among young adults compared to older adults (rated as 3.3 (max: 4.0, min: 2.0) and 2.4 (max: 4.0, min: 1.0), respectively). Participants also reported factors that restricted engagement or interest in HIIE. Both older and young adults noted "not enough time to exercise" as a moderate concern, with a rating of 2.4 (max: 3.0, min: 2.0) and 2.8 (max: 4.0, min: 2.0), respectively. Older adults also indicated that "lack of exercise knowledge" was a moderate concern with a rating of 2.4 (max: 3.0, min: 1.0), while young adults provided a mean rating of 1.3 (max: 2.0, min: 1.0). Lack of confidence in physical ability, musculoskeletal concerns and major health concerns were not strong negative influencing factors among either age group.

Table 3.7: Factors influencing interest and engagement in high-intensity interval exercise, presented as mean ± SD or *n* (%).

Survey Questions	**Older Adults (n = 5)**	**Young Adults (n = 6)**
First time engaging in HIIE *n (%)*	4 *(80%)*	1 *(16.7%)*
Enjoyment of in-lab HIIE*	4.2 ± 0.8	4.3 ± 0.5
Positive factors that increase interest in HIIE		
Musculoskeletal benefits	3.8 ± 0.5	4.0 ± 0.0
Cardiovascular benefits	3.6 ± 0.5	3.5 ± 0.8
Motivational / mood benefits	3.4 ± 0.5	3.2 ± 0.8
Time-efficiency benefits	2.4 ± 1.1	3.3 ± 0.8
Negative factors that decrease ability to perform / interest in HIIE		
Not enough time to exercise	2.4 ± 0.6	2.8 ± 0.8
Lack of exercise knowledge**	2.4 ± 0.9	1.3 ± 0.5
Lack of confidence in physical ability	1.8 ± 0.8	1.3 ± 0.5
Musculoskeletal concerns	1.4 ± 0.6	1.5 ± 0.6
Major health concerns	1.4 ± 0.5	1.0 ± 0.0

Scores based on means of scale ranging from 1 (not at all) to 4 (extremely).
*Scale for enjoyment of in-lab HIIE ranges from 1 (strongly disliked) to 5 (strongly enjoyed).
** Trend towards significant difference between groups, *p* = 0.55.

3.5 Discussion

This study compared the effects of an acute bout of HIIE on executive functions and affect among young and older adults. The study was underpowered; however, the preliminary results suggest that a single bout of HIIE might elicit different cognitive and affective changes depending on age group. Older adults did not show significant improvements in inhibition or working memory following HIIE compared to the control session, although z-scores showed a trend towards inhibitory improvement across conditions. Young adults demonstrated significant exercise-induced improvements in working memory performance but not inhibition. An improvement in post-exercise information processing speed was also observed for the whole sample. Although changes in positive affect were not significant, young adult participants elicited greater changes in exhaustion levels during the exercise session (higher exhaustion than older adults pre-exercise but similar post-exercise) and higher tranquility during the exercise session. These preliminary findings suggest that HIIE may improve working memory, tranquility and exhaustion levels but primarily among young adults. Firm conclusions should not be made from these results based on the limited sample size of this study; however, results may be useful to guide the hypotheses, purpose and methodology of future cognition and affect-focused HIIE studies.

During all conditions of the Stroop task (congruent, neutral, incongruent), young adults exhibited greater performance (as demonstrated by lower RT_{LISAS} scores) than older adults. This result was expected, as previous literature has frequently recognized that inhibitory control tends to decline during later life (Diamond, 2013; Wasylyshyn et al., 2011). Neither age group demonstrated significant changes in inhibition during the exercise or control conditions, although older adults trended towards greater improvement compared to young adults. These findings align with that of Kamijo et al. (2009) in which young adults responded faster than older adults in both the congruent and incongruent conditions of the Stroop task, but neither group demonstrated greater overall improvement from pre-exercise to post-exercise compared to a control condition. Although no published studies have examined the influence of HIIE on inhibition with more than one age group, HIIE has been shown to elicit a positive effect on inhibition compared to a control session among middle-to-older adults ($d = 0.53$) and young adults ($d = 0.44$) (Alves et al., 2012; Kao et al., 2018). It is possible that this study was underpowered to detect a significant effect of HIIE on inhibitory control across age groups, therefore, the interpretation of these findings may not be an accurate representation of a true cognitive response to HIIE. On the other hand, it is also possible that differences were due to mental fatigue potentially experienced by participants from the multiple cognitive assessments completed during each session (Grady, 1998; Martins et al., 2015). This study required participants to complete two distinct cognitive tests, each comprised of multiple tasks with varying difficulty levels, at three separate timepoints per session. Participants may have therefore faced mental fatigue in completing the tasks periodically throughout each session, thus influencing their cognitive performance.

Due to the small sample size, it is difficult to interpret results as supporting or refuting our hypotheses. However, the results do not align with the first two hypotheses that proposed improvements in inhibition with exercise and a larger magnitude of improvements among older adults. Although the interaction between condition, timepoint, and age group neared significance ($p = 0.09$), post hoc analysis did not suggest a significant exercise effect on inhibition in either age group. The hypothesis was based on the results of meta-analyses, which suggested that inhibition improved with exercise and that general cognitive improvements were greater among older adults (Chang et al., 2012; Ludyga et al., 2016). A lack of an exercise-effect on inhibition may be due to the significant variability among individual RT_{LISAS} scores in this small sample. Variability in RT_{LISAS} scores may have been accentuated in the current study due to individual responses to the prolonged cognitive testing, especially among older adults. Variability was especially dominant within the older adult sample and likely reflected an overload of cognitive resources (increase in cognitive fatigue and task demands) during the incongruent Stroop task (Lorist et al., 2005). Older adults also demonstrated a significant change in Z-scores during the incongruent task whereas young adults did not, suggesting that older adults may have exhibited notable improvements in RT_{LISAS} scores, had confounding factors not been as prevalent. It is also important to note that the fitness level of older adults within this study was very high. Given that higher fitness levels are often associated with enhanced executive functions in older adults, it is possible that the cognitive level of our sample at baseline may have been higher than that of lower-fit participants in prior studies that found significant benefits (Diamond, 2013; Guiney & Machado, 2012). The fitness level of participants may have therefore resulted in a smaller magnitude of improvement compared to studies with greater variability in fitness levels.

In this study, young adults demonstrated superior working memory performance compared to older adults, which was expected. Previous literature has identified a significant age difference in the performance of working memory tasks between young and older adults, often due to cognitive decline commonly observed during later life (Hogan et al., 2013; Perkash et al., 2012). Young adults also exhibited an improvement in working memory across timepoints only during the exercise condition, whereas no change was observed in the control session or among older adults in either session, opposing our second hypothesis. Hypothesis 2 suggested that working memory would improve with exercise and that improvements would be greater among older adults. As there is no published research regarding HIIE on working memory among older adults, hypothesis 2 was partly based on the findings of Cordova and colleagues (2009) who examined the influence of high-intensity continuous exercise on working memory among 48 physically active older adults. They observed a small positive improvement in working memory after high-intensity continuous exercise (*d* = 0.18). Since other studies have suggested that improvements in executive functioning may be greater following HIIE compared to high-intensity continuous exercise (Gibala et al., 2012; Moore et al., 2012), it was reasonable to expect that older adults would improve working memory following HIIE. An additional source of the discrepancy within the current study results may be due to the majority of older adults having never performed HIIE prior to the in-lab session. It is possible that exposure to a novel intervention may have increased cognitive demands and anxiety during the exercise (Allender et al., 2006; Franco et al., 2015). As a result, arousal and the subsequent task performance of older adults during the working memory task may have been adversely affected. Future HIIE research should consider the influence of a novel vs practiced exercise intervention when assessing its influence on cognitive performance. This may reduce the level of cognitive demand faced by participants, ensuring that the exercise intervention is applied with the intention of enhancing cognitive performance, rather than diminishing it.

From a neuroanatomical perspective, another potential cause of the age-specific improvement in working memory could be due to an increase in BDNF levels that tend to influence the cortical areas utilized during a working memory test. An upregulation of BDNF has been identified in the hippocampus and surrounding areas (such as the striatum) following exercise, which are regions highly engaged during tasks of working memory (Leckie et al., 2014; Llorens-Martín et al., 2008). Studies have found an increased expression of serum BDNF following HIIE compared to moderate-intensity exercise, which has been associated with improved cognitive performance (Ferris et al., 2007; Saucedo Marquez et al., 2015). It is possible that the HIIE protocol in this study may have elicited a positive influence on BDNF-mediated brain function and cognitive performance among young adults. These cortical regions (hippocampus, striatum) also tend to show a prominent decline in structural integrity with aging and are highly vulnerable to age-related cortical deterioration (Fjell et al., 2016; Grady, 2012; Sasson et al., 2013). Therefore, tasks requiring the involvement of the hippocampus and surrounding areas may not be subject to the same level of improvement following a high-intensity protocol among older adults compared to young adults, although further research is needed to explore this in greater detail.

During the exercise condition of the current study, young adults exhibited significantly improved simple information processing (0-back RT_{LISAS} scores) from pre-activity to post-activity, while older adults trended towards a significant improvement from pre-activity to the delay period. No performance changes were observed in the control condition. An increase in information processing speed can be a highly beneficial cognitive improvement, as it allows humans to be agile and reactive in real-life settings, such as when driving, walking in a busy area or in a sport environment (Oppenheimer & Kelso, 2015). Faster information processing has been previously observed after high-intensity exercise (Kujach et al., 2018). It is possible that exercise-induced cognitive improvements may be a result of enhanced neuronal activity (i.e., a greater firing of excitatory neurons), potentially due to a post-exercise influx of hormones such as dopamine and noradrenaline that increase neuronal excitability (De Beaumont et al., 2007; Kamijo et al., 2007; Kao et al., 2018). An increase in neuronal excitability is believed to influence speed of information processing, as observed in a recent study by Kao and colleagues (2018). Using EEG, Kao et al. (2018) observed a post-exercise increase in P3 latency (believed to represent information processing speed) alongside an associated decrease in response time during a simple response time task.). Moreover, the increased variability in cognitive performance among older adults within this study may have also influenced the age-specific differences observed in the information processing results.

Our third hypothesis anticipated that both young and older adults would demonstrate increased levels of positive affect, exhaustion and tranquility following HIIE; however, there was no change in positive affect following HIIE. Studies measuring the influence of HIIE on positive affect often measure affective behaviour during and following HIIE, whereas none have exclusively measured affect following a HIIE intervention, making it difficult to establish a conclusive effect of HIIE on post-exercise affect (Jung et al., 2013; Malik et al., 2019; Thum et al., 2017). The current results are in contrast to those of Jung and colleagues (2013) who found a decrease in positive affect immediately following a HIIE intervention. In this prior study, affect scores were also continuously measured during the exercise intervention (with affect significantly decreasing throughout) so it is possible that consecutive measurement over a short time period could have induced sensitivity towards the test answers. To reduce the influence of potential confounding variables, future research focused on HIIE and affect should consider the impact of measurement timing (pre-exercise, during, post-exercise) on the findings.

Analysis of the additional affective sub-scales revealed that young adults demonstrated significantly greater scores of overall physical exhaustion compared to older adults, alongside a positive change in physical exhaustion from pre-exercise to post-exercise. Young adults also had a greater overall score of tranquility during the exercise condition compared to the control condition. Older adults did not reveal any changes in physical exhaustion or tranquility. These findings may have been influenced by the fatiguing lifestyle and high demands of young adult university students (Lee et al., 2013). Previous literature has suggested that young adults often engage in exercise as a way to calm down and remove themselves from external stressors (Steltenphol et al., 2019). The high level of tranquility and positive change in physical exhaustion levels during the HIIE session seem to coincide with the psychological motivators noted in the literature.

When reflecting back on their participation, both age groups found the HIIE session to be highly enjoyable. Previous studies examining the enjoyment levels of HIIE have discovered that HIIE elicits greater levels of enjoyment compared to high- and moderate-intensity continuous exercise, with an effect size of $d = 0.43$ favouring HIIE (Jung et al., 2013; Thum et al., 2017). Exercise engagement and adherence can be strongly influenced by the perception that one holds towards the activity; if it is highly disliked, the chance of one continuing their participation is slim (Steltenphol et al., 2019). The high level of HIIE enjoyment among individuals of different age groups within this study supports the benefit of HIIE on enjoyment levels and potential exercise adherence.

As a secondary investigation in this study, the perceived barriers and supports to HIIE engagement were examined. Both young and older adults noted that "lack of time" was a moderate barrier to exercise engagement, which is a common cause of inactivity among young adults but less-so among older adults (Schutzer & Graves, 2004; Spiteri et al., 2019). Anxiety and lack of confidence towards exercise participation are also common barriers faced by young adults, but these factors were not noted as significant barriers in our sample group (Allender et al., 2006). The absence of confidence-related barriers identified by young adults in the current study is likely due to participant's high levels of exercise experience and fitness, resulting in greater exercise confidence compared to their less-active peers. In contrast, older adults revealed that lack of exercise knowledge and confidence were slight-to-moderate barriers for HIIE engagement, which reflects the findings of a recent systematic review that identified "beliefs about capabilities" as a primary barrier to exercise participation among older adults (Spiteri et al., 2019). Although older adults often cite poor health as a leading barrier to exercise participation, this was not the case in the current study (Franco et al., 2015; Schutzer & Graves, 2004). The older adult sample in this study was highly active and did not reveal any significant health-related barriers. Since the participant group had good-to-excellent overall health status, the primary concerns regarding HIIE revealed in this study are likely not representative of the entire population and should only be considered for active, healthy adults.

Among both age groups, the two strongest factors that increased interest in HIIE were musculoskeletal and cardiovascular benefits. Improvements in physical health have been noted as prominent motivators for exercise within the literature, as they offer a wide range of opportunities for enhanced quality of life among young and older adults, including weight control, ability to partake in physical activities (e.g., playing with grandchildren, walking outside), improved sleep and stress relief (Allender et al., 2006; Franco et al., 2015). Motivational and mood benefits were highly ranked among participants, reflecting a similar finding to that of recent literature in which “reinforcement” (i.e., enjoyment and gratification of exercising) has been identified as a top-rated motivator to exercise participation (Spiteri et al., 2019; Steltenpohl et al., 2019). Time-efficiency benefits were also a prominent support for HIIE among participants, although time-efficiency was a more influential factor for young adults compared to older adults. Since “lack of time” is often highlighted as a primary barrier to exercise participation (both in the current study and previous literature) the time-efficiency benefits of HIIE support the importance of this activity as an alternative to traditional exercise protocols (e.g., MICE), while still inducing the physical, cognitive, and/or mood benefits of exercise in a shorter time frame.

3.6 Strengths

The design of this study has some strengths. First, a graded exercise test was used to measure participant’s fitness levels and maximum HR. In doing so, HRR (which takes into account maximum & resting HR) was able to assist in determining a target HR that was individual to each participant. Many exercise studies use the age-predicated maximum HR to determine target HR; however, this method often results in an inaccurate estimation of the true target HR (Arena et al., 2016). This study also aimed to improve internal validity by ensuring that young and older adults participated in their sessions at the time of day associated with higher cognitive alertness for each age group (Anderson et al., 2014). This was done to reduce the possibility of inherently lower arousal levels impacting the performance of executive functions.

Finally, the use of a validated computer-based version of the Stroop and n-back tasks allowed for detailed trial-by-trial measurement of response time and accuracy. While paper-administered cognitive tasks tend to be less time-consuming to produce and administer, they do not provide the valuable precision that computer-based methods offer (Wahlstrom, 2017).

3.7 Limitations

There are several limitations to this study that warrant discussion. First, this study was unable to reach the target number of participants, with only 35% of the anticipated sample size having completed all three sessions prior to the closure of the study. As a result, this study was underpowered to detect differences due to exercise across age groups. In addition, the sample included highly fit and active individuals, so the findings of this study cannot be generalized to the broader population. This study also included predominantly female participants in the older adult group, which may have influenced the external validity of our results and comparisons across age groups due to possible sex-specific differences in cognition and exercise-related effects (Munro et al., 2012). Additionally, the in-lab environment was highly controlled to improve internal validity, which limits the generalizability of the findings to real-life contexts such as gym and community settings. Finally, the online survey was distributed to participants at approximately 6 months post-intervention and only received a response rate of 73%. It is very likely that respondents had difficulty accurately answering questions related to their HIIE experience due to the large time gap between the in-lab session and survey distribution. Survey data should therefore be interpreted with caution, as it may not reflect participant’s perceptions towards HIIE with full accuracy.

3.8 Conclusion & Future Directions

This study was the first to examine the influence of HIIE on multiple executive functions and affect in both young and older adults. An acute bout of HIIE elicited improvements in working memory among young adults but not older adults, while inhibition did not appear to be positively impacted by HIIE in either age group. Speed of information processing improved among both young and older adults following the HIIE intervention, whereas no changes were noted in the control condition. There were no significant post-exercise improvements in positive affect; however, young adults demonstrated a positive change in physical exhaustion scores from pre-exercise to post-exercise, as well as greater levels of tranquility during the exercise session compared to the control session. The results of this study should be used to help inform the methodology, purpose and hypotheses for future HIIE studies. First, the effects of HIIE on cognitive performance may vary by age groups, therefore, studies should include and be powered to compare young and older adults. In addition, since HIIE effects varied by component of executive function, future studies should probe further to understand the specificity of exercise effects. By utilizing the abovementioned suggestions in future studies, the cognitive and affective benefits of HIIE can be properly investigated with greater clarity and confidence. In doing so, health promotion strategies to augment cognitive health using exercise can be better targeted towards specific populations and abilities.

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Appendix A

A.1 Physical Activity Affect Scale

Participant ID:____________________Session:__________Day:________Time: _________

Physical Activity Affect Scale (PAAS)

Instructions: Please use the following scale to indicate the extent to which each word below described **how you feel at this moment in time**. Record your responses by circling the appropriate number.

	Do Not Feel	Feel Slightly	Feel Moderately	Feel Strongly	Feel Very Strongly
1. Upbeat	0	1	2	3	4
2. Calm	0	1	2	3	4
3. Energetic	0	1	2	3	4
4. Tired	0	1	2	3	4
5. Peaceful	0	1	2	3	4
6. Miserable	0	1	2	3	4
7. Worn-Out	0	1	2	3	4
8. Relaxed	0	1	2	3	4
9. Fatigued	0	1	2	3	4
10. Discouraged	0	1	2	3	4
11. Enthusiastic	0	1	2	3	4
12. Crummy	0	1	2	3	4

A.2 Online Survey Questionnaire

Thesis Survey Questions

This survey will ask you questions related to your experience and perception of high-intensity interval exercise, as well as moderate intensity continuous exercise.

For your reference:

High-intensity interval exercise is defined as “short bursts of vigorous exercise, separated by periods of low-intensity activity for recovery”. Examples include: vigorous interval training via running, biking, swimming or cross-fit.

Moderate-intensity continuous exercise is defined as “exercise at a continuous, moderate-intensity”. Examples include: brisk walking, jogging, water aerobics, or lane swimming.

1) What is your participant number? [text box]

2) Was this study the first time you’ve engaged in high-intensity interval exercise?

- ○ Yes [if yes, skip to question 3]
- ○ No

3) How often did you engage in high-intensity interval exercise prior to the study?

- ○ 3x a week or more
- ○ 1-2x a week
- ○ 2-3x a month
- ○ Once a month
- ○ Less than once a month

4) What was your perception towards the high-intensity interval exercise in the lab?

- ○ I strongly liked it
- ○ I slightly liked it
- ○ I felt neutral – neither liked or disliked it
- ○ I slightly disliked it
- ○ I strongly disliked it

5) How did your experience in the study make you feel about doing high-intensity interval exercise in the future?

- ○ I do not want to participate in high-intensity interval exercise in the future.
- ○ I’d consider participating in high-intensity interval exercise in the future.
- ○ I would like to participate in high-intensity interval exercise in the future.
- ○ I have taken up high-intensity interval exercise since completing the study.

6) Have you engaged in high-intensity interval exercise since the study?

- Yes
- No [skip to question 7]

7) How often do you engage in high-intensity interval exercise currently? (note: if your physical activity levels have changed due to COVID-19 restrictions, please think back to your regular activity level prior to the pandemic)

- 3x a week or more
- 1-2x a week
- 2-3x a month
- Once a month
- Less than once a month

8) Have you engaged in moderate intensity continuous exercise since the study?

- Yes
- No [skip to question 9]

9) How often do you engage in moderate-intensity continuous exercise currently? (note: if your physical activity levels have changed due to COVID-19 restrictions, please think back to your regular activity level prior to the pandemic)

- 3x a week or more
- 1-2x a week
- 2-3x a month
- Once a month
- Less than once a month

10) When comparing moderate-intensity continuous exercise to high-intensity interval exercise, do you find that you tend to enjoy one type of exercise method over the other?

- I prefer moderate-intensity continuous exercise
- I prefer high-intensity interval exercise
- I don’t have a preference between the exercises
- Other: [text box]

11) If applicable, please provide a short explanation as to why you may prefer one type of exercise over the other: [text box]

12) How much do the following negative factors restrict your ability to do / interest in doing high intensity interval exercise?

	Extremely	**Moderately**	**Slightly**	**Not at all**
Musculoskeletal concerns (e.g., worried about aggravating existing injury)				
Major health concerns (e.g., worried about heart complication)				
Lack of knowledge (e.g., unsure of how to engage in HIIE without guidance)				
Lack of confidence in physical ability (not feeling “fit” enough to engage in HIIE)				

13) How much do the following positive factors increase your interest in doing high intensity interval exercise?

	Extremely	**Moderately**	**Slightly**	**Not at all**
Musculoskeletal benefits (e.g., greater muscle strength, balance or muscle tone)				
Cardiovascular benefits (e.g., increased cardiovascular fitness and heart health)				
Motivational / Mood benefits (e.g., pride in accomplishing a challenging workout)				
Time-efficiency benefits (e.g., fitting a quick workout into a busy day)				

14) How often is "not having enough time" a factor in missing workouts?

○ Very Often
○ Often
○ Sometimes
○ Seldom
○ Never

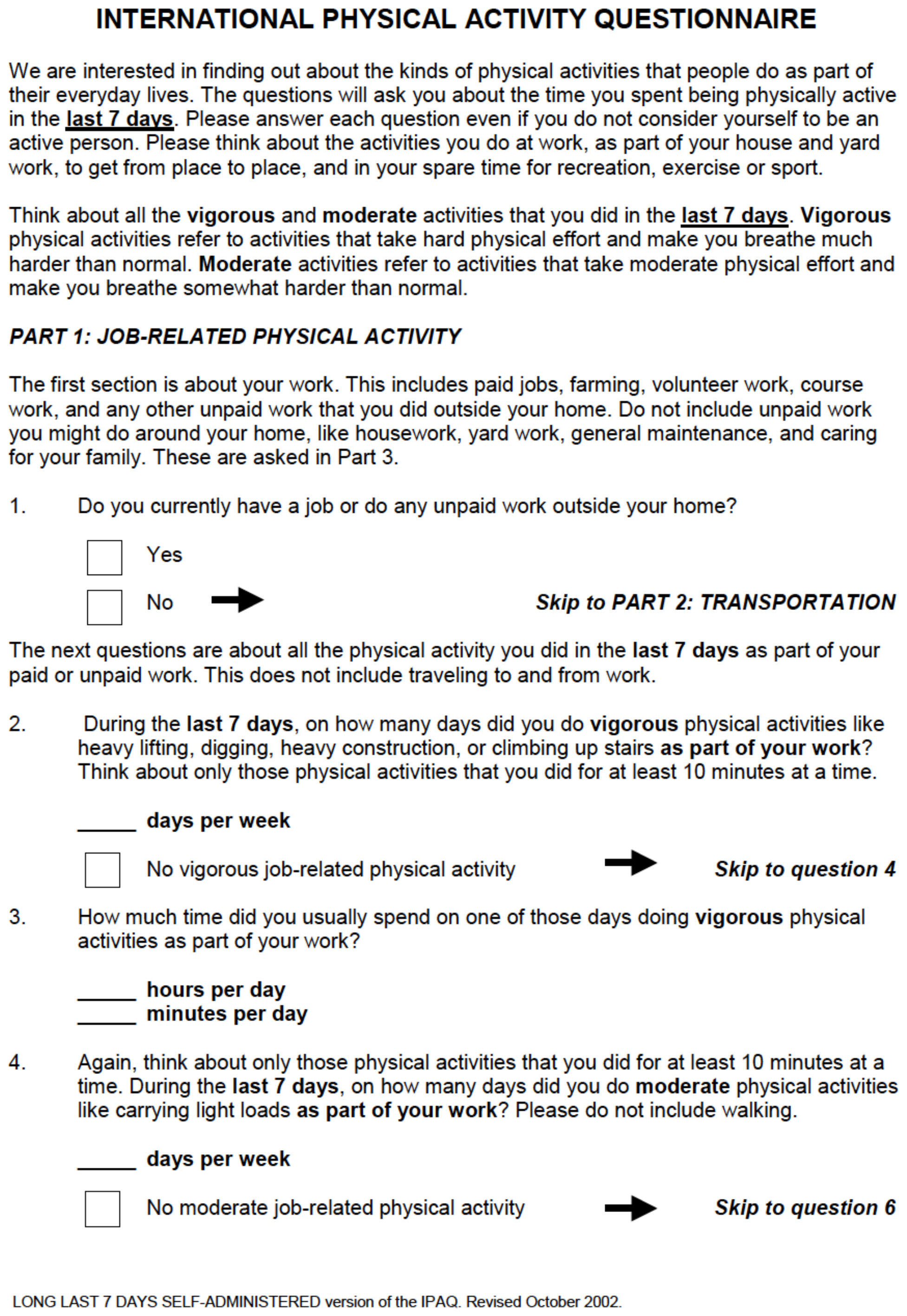
15) Please add any additional comments you may have regarding your experience(s) with high-intensity interval exercise: [text entry]

16) Would you be willing to talk to the researcher in a follow-up interview to better understand your experience with, and perception of high intensity interval exercise? The interview will contain questions related to your survey responses, as well as data collected during the in-lab sessions. The interview can occur either through an online video call, telephone, or the interviewer can provide the list of questions to be answered through written response. The interview will take no longer than 30 minutes.

- Yes, please provide your preferred e-mail address for contact: **____**[text entry]
- No [skip to the end of the survey]

End of Online Survey

A.3 International Physical Activity Questionnaire – Long Form



INTERNATIONAL PHYSICAL ACTIVITY QUESTIONNAIRE

We are interested in finding out about the kinds of physical activities that people do as part of their everyday lives. The questions will ask you about the time you spent being physically active in the **last 7 days**. Please answer each question even if you do not consider yourself to be an active person. Please think about the activities you do at work, as part of your house and yard work, to get from place to place, and in your spare time for recreation, exercise or sport.

Think about all the **vigorous** and **moderate** activities that you did in the **last 7 days**. **Vigorous** physical activities refer to activities that take hard physical effort and make you breathe much harder than normal. **Moderate** activities refer to activities that take moderate physical effort and make you breathe somewhat harder than normal.

PART 1: JOB-RELATED PHYSICAL ACTIVITY

The first section is about your work. This includes paid jobs, farming, volunteer work, course work, and any other unpaid work that you did outside your home. Do not include unpaid work you might do around your home, like housework, yard work, general maintenance, and caring for your family. These are asked in Part 3.

1. Do you currently have a job or do any unpaid work outside your home?

☐ Yes
☐ No → ***Skip to PART 2: TRANSPORTATION***

The next questions are about all the physical activity you did in the **last 7 days** as part of your paid or unpaid work. This does not include traveling to and from work.

2. During the **last 7 days**, on how many days did you do **vigorous** physical activities like heavy lifting, digging, heavy construction, or climbing up stairs **as part of your work**? Think about only those physical activities that you did for at least 10 minutes at a time.

_____ **days per week**

☐ No vigorous job-related physical activity → ***Skip to question 4***

3. How much time did you usually spend on one of those days doing **vigorous** physical activities as part of your work?

_____ **hours per day**
_____ **minutes per day**

4. Again, think about only those physical activities that you did for at least 10 minutes at a time. During the **last 7 days**, on how many days did you do **moderate** physical activities like carrying light loads **as part of your work**? Please do not include walking.

_____ **days per week**

☐ No moderate job-related physical activity → ***Skip to question 6***

LONG LAST 7 DAYS SELF-ADMINISTERED version of the IPAQ. Revised October 2002.

5. How much time did you usually spend on one of those days doing **moderate** physical activities as part of your work?

_____ **hours per day**
_____ **minutes per day**

6. During the **last 7 days**, on how many days did you **walk** for at least 10 minutes at a time **as part of your work**? Please do not count any walking you did to travel to or from work.

_____ **days per week**

☐ No job-related walking → ***Skip to PART 2: TRANSPORTATION***

7. How much time did you usually spend on one of those days **walking** as part of your work?

_____ **hours per day**
_____ **minutes per day**

PART 2: TRANSPORTATION PHYSICAL ACTIVITY

These questions are about how you traveled from place to place, including to places like work, stores, movies, and so on.

8. During the **last 7 days**, on how many days did you **travel in a motor vehicle** like a train, bus, car, or tram?

_____ **days per week**

☐ No traveling in a motor vehicle → ***Skip to question 10***

9. How much time did you usually spend on one of those days **traveling** in a train, bus, car, tram, or other kind of motor vehicle?

_____ **hours per day**
_____ **minutes per day**

Now think only about the **bicycling** and **walking** you might have done to travel to and from work, to do errands, or to go from place to place.

10. During the **last 7 days**, on how many days did you **bicycle** for at least 10 minutes at a time to go **from place to place**?

_____ **days per week**

☐ No bicycling from place to place → ***Skip to question 12***

11. How much time did you usually spend on one of those days to **bicycle** from place to place?

_____ **hours per day**
_____ **minutes per day**

12. During the **last 7 days**, on how many days did you **walk** for at least 10 minutes at a time to go **from place to place**?

_____ **days per week**

☐ No walking from place to place → ***Skip to PART 3: HOUSEWORK, HOUSE MAINTENANCE, AND CARING FOR FAMILY***

13. How much time did you usually spend on one of those days **walking** from place to place?

_____ **hours per day**
_____ **minutes per day**

PART 3: HOUSEWORK, HOUSE MAINTENANCE, AND CARING FOR FAMILY

This section is about some of the physical activities you might have done in the **last 7 days** in and around your home, like housework, gardening, yard work, general maintenance work, and caring for your family.

14. Think about only those physical activities that you did for at least 10 minutes at a time. During the **last 7 days**, on how many days did you do **vigorous** physical activities like heavy lifting, chopping wood, shoveling snow, or digging **in the garden or yard**?

_____ **days per week**

☐ No vigorous activity in garden or yard → ***Skip to question 16***

15. How much time did you usually spend on one of those days doing **vigorous** physical activities in the garden or yard?

_____ **hours per day**
_____ **minutes per day**

16. Again, think about only those physical activities that you did for at least 10 minutes at a time. During the **last 7 days**, on how many days did you do **moderate** activities like carrying light loads, sweeping, washing windows, and raking **in the garden or yard**?

_____ **days per week**

☐ No moderate activity in garden or yard → ***Skip to question 18***

17. How much time did you usually spend on one of those days doing **moderate** physical activities in the garden or yard?

_____ **hours per day**
_____ **minutes per day**

18. Once again, think about only those physical activities that you did for at least 10 minutes at a time. During the **last 7 days**, on how many days did you do **moderate** activities like carrying light loads, washing windows, scrubbing floors and sweeping **inside your home**?

_____ **days per week**

☐ No moderate activity inside home → ***Skip to PART 4: RECREATION, SPORT AND LEISURE-TIME PHYSICAL ACTIVITY***

19. How much time did you usually spend on one of those days doing **moderate** physical activities inside your home?

_____ **hours per day**
_____ **minutes per day**

PART 4: RECREATION, SPORT, AND LEISURE-TIME PHYSICAL ACTIVITY

This section is about all the physical activities that you did in the **last 7 days** solely for recreation, sport, exercise or leisure. Please do not include any activities you have already mentioned.

20. Not counting any walking you have already mentioned, during the **last 7 days**, on how many days did you **walk** for at least 10 minutes at a time **in your leisure time**?

_____ **days per week**

☐ No walking in leisure time → ***Skip to question 22***

21. How much time did you usually spend on one of those days **walking** in your leisure time?

_____ **hours per day**
_____ **minutes per day**

22. Think about only those physical activities that you did for at least 10 minutes at a time. During the **last 7 days**, on how many days did you do **vigorous** physical activities like aerobics, running, fast bicycling, or fast swimming **in your leisure time**?

_____ **days per week**

☐ No vigorous activity in leisure time → ***Skip to question 24***

23. How much time did you usually spend on one of those days doing **vigorous** physical activities in your leisure time?

_____ **hours per day**
_____ **minutes per day**

24. Again, think about only those physical activities that you did for at least 10 minutes at a time. During the **last 7 days**, on how many days did you do **moderate** physical activities like bicycling at a regular pace, swimming at a regular pace, and doubles tennis **in your leisure time**?

_____ **days per week**

☐ No moderate activity in leisure time → ***Skip to PART 5: TIME SPENT SITTING***

25. How much time did you usually spend on one of those days doing **moderate** physical activities in your leisure time?
_____ **hours per day**
_____ **minutes per day**

PART 5: TIME SPENT SITTING

The last questions are about the time you spend sitting while at work, at home, while doing course work and during leisure time. This may include time spent sitting at a desk, visiting friends, reading or sitting or lying down to watch television. Do not include any time spent sitting in a motor vehicle that you have already told me about.

26. During the **last 7 days**, how much time did you usually spend **sitting** on a **weekday**?

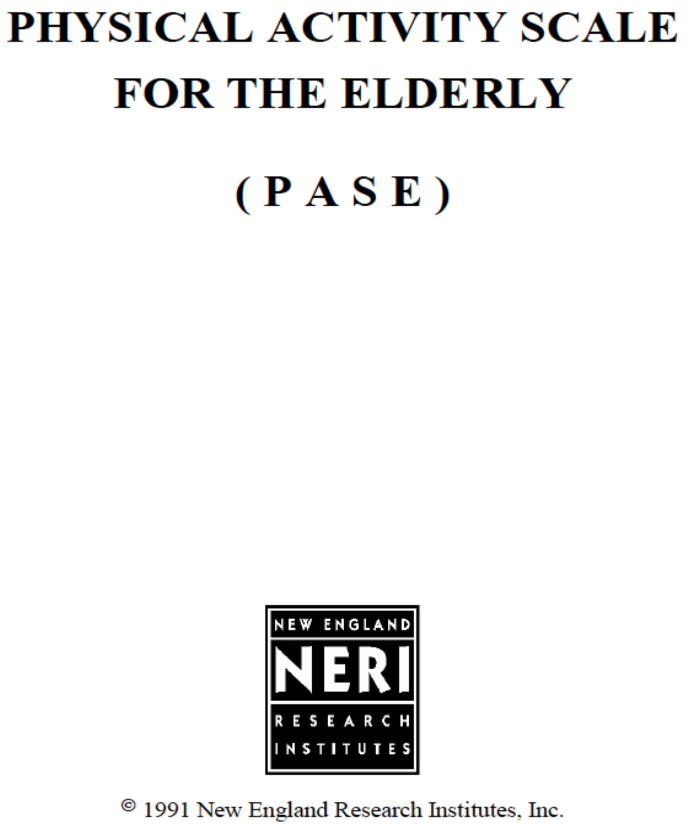
_____ **hours per day**
_____ **minutes per day**

27. During the **last 7 days**, how much time did you usually spend **sitting** on a **weekend day**?

_____ **hours per day**
_____ **minutes per day**

This is the end of the questionnaire, thank you for participating.

A.4 Physical Activity Scale for the Elderly



PHYSICAL ACTIVITY SCALE
FOR THE ELDERLY

(PASE)

INSTRUCTIONS:

Please complete this questionnaire by either circling the correct response or filling in the blank. Here is an example:

> During the past 7 days, how often have you seen the sun?

[0.] NEVER	[1.] SELDOM	[2.] SOMETIMES	[3.] OFTEN
	(1-2 DAYS)	(3-4 DAYS)	(5-7 DAYS)

Answer all items as accurately as possible. All information is strictly confidential.

LEISURE TIME ACTIVITY

1. Over the past 7 days, how often did you participate in sitting activities such as reading, watching TV or doing handcrafts?

[0.] NEVER	[1.] SELDOM	[2.] SOMETIMES	[3.] OFTEN
↓	(1-2 DAYS)	(3-4 DAYS)	(5-7 DAYS)
GO TO Q.#2	↓	↓	↓

1a. What were these activities?

____

1b. On average, how many hours per day did you engage in these sitting activities?

[1.] LESS THAN 1 HOUR	[2.] 1 BUT LESS THAN 2 HOURS
[3.] 2-4 HOURS	[4.] MORE THAN 4 HOURS

2. Over the past 7 days, how often did you take a walk outside your home or yard for any reason? For example, for fun or exercise, walking to work, walking the dog, etc.?

[0.] NEVER	[1.] SELDOM	[2.] SOMETIMES	[3.] OFTEN
↓	(1-2 DAYS)	(3-4 DAYS)	(5-7 DAYS)
GO TO Q.#3	↓	↓	↓

2a. On average, how many hours per day did you spend walking?

[1.] LESS THAN 1 HOUR	[2.] 1 BUT LESS THAN 2 HOURS
[3.] 2-4 HOURS	[4.] MORE THAN 4 HOURS

3. Over the past 7 days, how often did you engage in light sport or recreational activities such as bowling, golf with a cart, shuffleboard, fishing from a boat or pier or other similar activities?

[0.] NEVER	[1.] SELDOM	[2.] SOMETIMES	[3.] OFTEN
↓	(1-2 DAYS)	(3-4 DAYS)	(5-7 DAYS)
GO TO Q.#4	↓	↓	↓

3a. What were these activities?

____

3b. On average, how many hours per day did you engage in these light sport or recreational activities?

[1.] LESS THAN 1 HOUR	[2.] 1 BUT LESS THAN 2 HOURS
[3.] 2-4 HOURS	[4.] MORE THAN 4 HOURS

4. Over the past 7 days, how often did you engage in moderate sport and recreational activities such as doubles tennis, ballroom dancing, hunting, ice skating, golf without a cart, softball or other similar activities?

[0.] NEVER	[1.] SELDOM	[2.] SOMETIMES	[3.] OFTEN
↓	(1-2 DAYS)	(3-4 DAYS)	(5-7 DAYS)
GO TO Q.#5	↓	↓	↓

4a. What were these activities?

____

4b. On average, how many hours per day did you engage in these moderate sport and recreational activities?

[1.] LESS THAN 1 HOUR	[2.] 1 BUT LESS THAN 2 HOURS
[3.] 2-4 HOURS	[4.] MORE THAN 4 HOURS

5. Over the past 7 days, how often did you engage in strenuous sport and recreational activities such as jogging, swimming, cycling, singles tennis, aerobic dance, skiing (downhill or cross-country) or other similar activities?

[0.] NEVER	[1.] SELDOM	[2.] SOMETIMES	[3.] OFTEN
↓	(1-2 DAYS)	(3-4 DAYS)	(5-7 DAYS)
GO TO Q.#6	↓	↓	↓

5a. What were these activities?

____

5b. On average, how many hours per day did you engage in these strenuous sport and recreational activities?

[1.] LESS THAN 1 HOUR	[2.] 1 BUT LESS THAN 2 HOURS
[3.] 2-4 HOURS	[4.] MORE THAN 4 HOURS

6. Over the past 7 days, how often did you do any exercises specifically to increase muscle strength and endurance, such as lifting weights or pushups, etc.?

[0.] NEVER	[1.] SELDOM	[2.] SOMETIMES	[3.] OFTEN
↓	(1-2 DAYS)	(3-4 DAYS)	(5-7 DAYS)
GO TO Q.#7	↓	↓	↓

6a. What were these activities?

____

6b. On average, how many hours per day did you engage in exercises to increase muscle strength and endurance?

[1.] LESS THAN 1 HOUR	[2.] 1 BUT LESS THAN 2 HOURS
[3.] 2-4 HOURS	[4.] MORE THAN 4 HOURS

HOUSEHOLD ACTIVITY

7. During the past 7 days, have you done any light housework, such as dusting or washing dishes?

[1.] NO [2.] YES

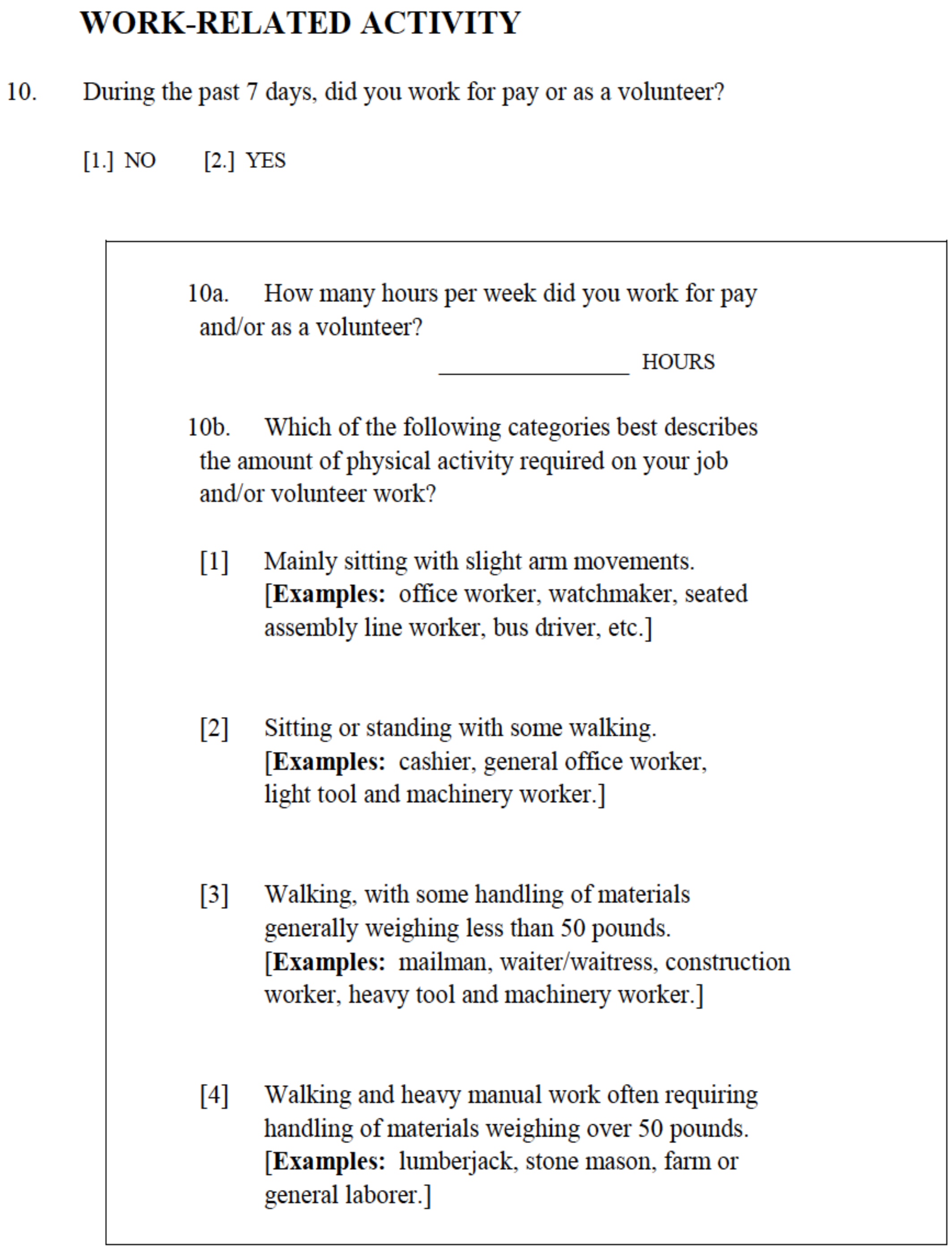
8. During the past 7 days, have you done any heavy housework or chores, such as vacuuming, scrubbing floors, washing windows, or carrying wood?

[1.] NO [2.] YES

9. During the past 7 days, did you engage in any of the following activities?

Please answer YES or NO for each item.

		NO	YES
a.	Home repairs like painting, wallpapering, electrical work, etc.	1	2
b.	Lawn work or yard care, including snow or leaf removal, wood chopping, etc.	1	2
c.	Outdoor gardening	1	2
d.	Caring for an other person, such as children, dependent spouse, or an other adult	1	2



WORK-RELATED ACTIVITY

10. During the past 7 days, did you work for pay or as a volunteer?

[1.] NO [2.] YES

10a. How many hours per week did you work for pay and/or as a volunteer?

________________ HOURS

10b. Which of the following categories best describes the amount of physical activity required on your job and/or volunteer work?

[1] Mainly sitting with slight arm movements. [**Examples:** office worker, watchmaker, seated assembly line worker, bus driver, etc.]

[2] Sitting or standing with some walking. [**Examples:** cashier, general office worker, light tool and machinery worker.]

[3] Walking, with some handling of materials generally weighing less than 50 pounds. [**Examples:** mailman, waiter/waitress, construction worker, heavy tool and machinery worker.]

[4] Walking and heavy manual work often requiring handling of materials weighing over 50 pounds. [**Examples:** lumberjack, stone mason, farm or general laborer.]

A.5 Supplementary Tables: Stroop Task

Table A.1: Group response time scores (ms) (mean ± SD) for the Stroop tasks across all conditions, timepoints and age groups.

Condition	**Exercise Session**			**Control Session**		
	Pre-activity	**Post-activity**	**Delay**	**Pre-activity**	**Post-activity**	**Delay**
			Young Adults			
Congruent	479.8 ± 51.2	458.7 ± 67.6	477.2 ± 63.1	517.7 ± 124.3	470.1 ± 34.8	462.8 ± 26.8
Neutral	519.2 ± 62.7	487.8 ± 56.1	504.9 ± 52.6	520.3 ± 79.6	494.1 ± 41.1	496.2 ± 38.5
Incongruent	567.4 ± 55.7	556.6 ± 48.5	527.5 ± 65	571.1 ± 94.5	560.7 ± 67.0	566 ± 66.0
			Older Adults			
Congruent	650.2 ± 53.1	592.6 ± 54.9	629.3 ± 63.7	627.8 ± 54.3	610.1 ± 52.9	605.8 ± 40.4
Neutral	657.1 ± 54.7	629.2 ± 61.9	645.4 ± 59.5	646 ± 75.3	655.4 ± 67.0	635.1 ± 66.9
Incongruent	899.1 ± 129.3	838.9 ± 92.2	847.5 ± 103.3	935.2 ± 181.7	886.5 ± 120.2	865.9 ± 114.1

Table A.2: Group percent error scores (%) (mean ± SD) for the Stroop tasks across all conditions, timepoints and age groups.

Condition	**Exercise Session**			**Control Session**		
	Pre-activity	**Post-activity**	**Delay**	**Pre-activity**	**Post-activity**	**Delay**
			Young Adults			
Congruent	0.8 ± 1.4	2.0 ± 3.1	1.2 ± 1.5	1.6 ± 2.2	1.6 ± 1.5	0.8 ± 1.4
Neutral	2.8 ± 2.3	2.4 ± 3.4	2.0 ± 2.1	1.6 ± 2.2	2.4 ± 3.0	2.4 ± 1.9
Incongruent	2.8 ± 2.3	3.2 ± 2.5	2.8 ± 2.8	2.8 ± 2.3	4.0 ± 3.5	4.8 ± 3.5
			Older Adults			
Congruent	0.0 ± 0.0	0.8 ± 1.4	0.8 ± 1.4	0.4 ± 1.1	0.4 ± 1.1	0.4 ± 1.1
Neutral	1.2 ± 1.5	0.4 ± 1.1	0.4 ± 1.1	0.4 ± 1.1	0.8 ± 1.4	0.0 ± 0.0
Incongruent	1.2 ± 1.5	1.6 ± 2.2	1.6 ± 2.2	2.4 ± 3.0	1.2 ± 2.2	1.2 ± 2.2

A.6 Supplementary Tables: N-back Task

Table A.3: Group response time scores (ms) (mean ± SD) for the n-back tasks across all conditions, timepoints and age groups.

Condition	**Exercise Session**			**Control Session**		
	Pre-activity	**Post-activity**	**Delay**	**Pre-activity**	**Post-activity**	**Delay**
Young Adults						
0-back	449.2 ± 51.9	410.5 ± 56.0	422.2 ± 54.0	440.7 ± 97.7	438.9 ± 66.3	426.2 ± 73.0
2-back	767.4 ± 238.4	590.5 ± 119.1	562.1 ± 90.8	704.9 ± 226.0	626.4 ± 171.8	613.4 ± 165.5
Older Adults						
0-back	582.1 ± 67.0	571.6 ± 80.5	543.1 ± 84.7	570.9 ± 94.5	553.0 ± 82.2	576.6 ± 86.9
2-back	902.2 ± 200.7	876.3 ± 194.8	864.1 ± 215.5	915.8 ± 258.8	929.5 ± 257.5	904.0 ± 227.6

Table A.4: Group percent error scores (%) (mean ± SD) for the n-back tasks across all conditions, timepoints and age groups.

Condition	**Exercise Session**			**Control Session**		
	Pre-activity	**Post-activity**	**Delay**	**Pre-activity**	**Post-activity**	**Delay**
Young Adults						
0-back	0.3 ± 0.7	0.5 ± 1.0	1.0 ± 1.1	1.3 ± 1.9	1.3 ± 1.6	0.3 ± 0.7
2-back	5.1 ± 4.1	2.7 ± 2.0	2.1 ± 1.7	5.1 ± 2.4	3.6 ± 1.6	4.2 ± 2.4
Older Adults						
0-back	0.9 ± 1.1	1.2 ± 1.7	0.3 ± 0.8	1.2 ± 1.6	1.2 ± 2.4	1.5 ± 1.6
2-back	9.1 ± 6.0	7.4 ± 4.5	8.0 ± 6.8	10.1 ± 5.3	8.7 ± 6.8	7.4 ± 7.0