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Numerous studies have examined how both chronic exercise engagement and single bouts of aerobic exercise impact cognitive functioning in a variety of populations. Across these studies it has been shown that single bouts of aerobic exercise have an enhancing effect on cognitive performance and that chronic exercise is positively associated with cognitive performance. Despite the promising research to date, few studies have examined the effects of acute or chronic exercise on older adults and even fewer have sought to examine the effects aging has on the exercise – cognition relationship. Therefore, the purpose of this dissertation was to examine how aging impacts the exercise – cognition relationship in two concurrently running studies. The purpose of study 1 was to examine if age group moderates the relationship between physical activity engagement and cognitive functioning. Study 1 was a cross-sectional design and consisted of one visit. Participants included both sedentary and physically active participants from age groups of young (20 – 30 years old) and older adults (60 – 70 years old). Participants filled out questionnaires assessing physical activity engagement and demographics and completed a battery of cognitive tasks assessing episodic memory and executive functioning. The purpose of study 2 was to examine how a single bout of moderate intensity aerobic exercise impacts episodic memory and executive functioning and to examine if aging moderates the effects. Study 2 was a mixed design with 3 visits. Participants included recreationally active (>90 mins/week) young (20 – 30 years old) and older adults (60 – 70 years old). Visits 2 and 3 were counterbalanced participation in a 20-min bout of aerobic exercise or resting for 20-mins on a cycle ergometer before completing tasks assessing episodic memory and executive functioning. In terms of cross-sectional associations, the results supported that age group had a significant

negative impact on memory and executive functioning, and that for both young and older adults' engagement in physical activity is beneficial for memory performance but not for executive functioning. Results also showed that following an acute bout of aerobic exercise there are significant enhancements in memory performance. In addition, for selected aspects of memory performance (learning and long-term memory) older adults benefited more from an acute bout of aerobic exercise compared to young adults. The results were mixed for executive functioning with select enhancements on inhibition. For the most difficult portion of the working memory task, older adults had significant improvements in their performance compared to young adults who showed no change. The current results indicate that for both young and older adults, physical activity engagement is positively related to memory performance which could indicate that both age groups stand to gain similar benefits. The results of study 2 show that older adults do indeed stand to gain more benefit from a single bout of aerobic exercise in terms of their episodic memory performance, and their ability to retain spatial information and manipulate remembered items in working memory. This is promising as numerous studies including this one have shown that older adults have diminished cognitive functioning and a behavioral treatment such as exercise could potentially counteract some of these deficits related to aging.

THE EFFECTS OF EXERCISE ON COGNITIVE FUNCTIONING: THE MODERATING ROLE OF AGING

by

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CHAPTER I: BACKGROUND

Statement of the problem

Throughout the normal aging process, individuals will experience age-related cognitive declines (ARCD) in a variety of cognitive skills. ARCD can begin as early as our 30's with individual variations in terms of the start of the decline (Cansino et al., 2013; Salthouse, 2009). For many individuals, these ARCD might not even be noticeable in their everyday lives. Despite that, our skills at remembering things and our ability to multi-task, be attentive when required, or interpret and solve problems will diminish with age. This can be the normal cognitive aging that a vast majority of individuals go through, or it can be more severe such as with mild cognitive impairment (MCI) or clinical in nature such as with Alzheimer's disease or other types of Dementia. ARCD does not just cost individuals their activities of daily lives, there is a financial cost of ARCD. The healthcare costs of MCI have been found to be $3,500 more per year than costs for individuals with no cognitive impairment (Zhu, et al., 2013). It was reported that more than 16 million Americans lived with MCI in 2011, resulting in an estimated additional $56 billion yearly for healthcare costs (Centers for Disease Control [CDC], 2011).

With the older adult population continually growing, developing cost-effective interventions to minimize healthcare costs associated with cognitive impairment are critical. Gaining a better understanding of how exercise can be utilized as a behavioral strategy for dealing with ARCD is vital so we can best utilize exercise to impact both normal and clinical cognitive decline. This is vital because an individual's cognitive functioning affects how they interact with their everyday environment. For example, MCI has been shown to be predictive of poorer self-care when it comes to remembering to take medications correctly (Cameron et al., 2010) and reduced health-related quality of life (Teng et al., 2012). To have a better understanding as to how exercise can be utilized to slow down the rate of ARCD, multiple steps are required. Not only do researchers need to conduct randomized-control trials examining how months or years of exercise engagement impact cognitive changes, but to better utilize chronic exercise more information is needed as to how single sessions of exercise impact cognition. By better understanding how single sessions of exercise affect cognition, we can better prescribe the daily bouts participants should be engaging in over a period of months or years such as in intervention studies.

The effects of aging on cognitive functioning

Episodic memory

A large body of research has been completed in cognitive psychology examining how aging impacts varying cognitive domains differently. One of these cognitive domains is episodic memory which is an individuals' ability to recall specific episodes or information associated with those episodes (Hudson et al., 2011). Something of note for episodic memory is its uniqueness in terms of it being broken up into multiple phases (encoding, consolidation, and recall/recognition; Huijbers, 2010). Encoding is when the participant is exposed to the information initially. Encoding is followed by consolidation which is a category of processes that stabilize a memory trace after its initial acquisition to attempt to turn the information into long-term memories. Finally recall is the participants' capability to retrieve the aforementioned items they originally encoded from their memory, and recognition is their ability to "recognize" the items they were exposed to as being familiar to them but not recalling them from their own memory. Previous work examining episodic memory has been broken up into two different task types. The first is single-item episodic memory where individuals are required to remember a list of words or numbers as singular entities not necessarily paired or bound to any other items (Naveh-Benjamin et al., 2003; Ratcliff et al., 2011; Verhaeghen et al., 1998). The second is associative episodic memory where individuals are required to learn novel bindings between two items such as (SHARK – gun, or LAMP – fish) and be able to remember the second word when exposed to the first word of the bound pair or a variation of that (Arndt, 2012; Buchler & Reder, 2007; Craik, 1983, 1986; Healy et al., 2005; Old & Naveh-Benjamin, 2008).

Research examining single-item episodic memory has found that older adults perform significantly worse than young adults (Naveh-Benjamin et al., 2003; Ratcliff et al., 2011; Verhaeghen et al., 1998). A good example of this is research completed by Naveh-Benjamin (2003) across two studies. For Study 1, Naveh-Benjamin et al. (2003) had 36 younger and 18 older adults that were assigned to one of three groups. The young adults were randomly assigned to young adults' full attention (M =24.3 years) or young adults divided attention (M= 22.8 years), and the older adults were all assigned to full attention (M= 76.2 years). Each participant was exposed to a list of picture pairs in the study phase. In the full attention group, participants were instructed to learn each pair in order to prepare for tests on the information. Participants in the divided attention group were given the same instructions and, also told to perform a concurrent digit-detection task as accurately as possible. Once completed, there were 60 seconds before item- and associative-recognition tasks were completed. To assess differences across the different conditions, they computed a discrimination measure based on hit and false-alarm rate (A'). This made it possible to compare the item- and associative-recognition tests across conditions (higher scores indicate better performance). They found that the older adult group was disproportionally affected on the association test (A' = .69) relative to the item test (A' = .89) compared with younger adults' full attention (A' = .93 and .95). In Study 2, Naveh-Benjamin et al. (2003) included word pairs that were unrelated or related semantically and tested them using the same procedures. Study 2 included 60 young adult and 30 older adult participants. As with study 1, participants were randomly assigned to young adult full attention (M=21.4 years), young adult divided attention (M= 22.6 years), and older adults full attention (M= 73.7 years). They found that older adults' memory performance was significantly impaired on the associative test (A' = 0.42) for unrelated pairs compared to the item test (A' = 1.70); this was not the case for related associative pairs. For the related pairs, memory performance of the older adults was not significantly different on the associative test (A' = 1.69) relative to the item test (A' = 1.52). They also found the older adults' performance was still significantly worse compared to the full attention young adults on both item and associative pairs.

In another study examining how aging impacts single-item episodic memory free and cued recall, Verhaeghen et al. (1998) conducted 2 experiments. Study 1 included 13 young (M=20.8 years) and 13 older (M=63.9 years) adults. They had participants complete a memory task consisting of 36 lists of 12 Dutch words. Twelve wordlists were presented with no cues. Twelve wordlists were presented with rhyme cues (Example would be: able TABLE). Twelve wordlists were presented with semantic cues (Example would be: food TABLE). An arithmetic task lasting roughly 20 seconds was completed between studying of the wordlists and recall. Following the arithmetic task, participants were requested to type all the words they could remember. In the cued conditions, all 12 of the cues remained visible during recall. They found that age group significantly affected the maximum level of performance attainable and the rate of approach toward their maximum attainable performance (slope of the curve). Study 2 included 29 young (M=22.4 years) and 30 older (M=64.2 years) adults and 4 conditions. The memory task consisted of a total of 48 lists of 15 Dutch words. In the baseline condition, 12 wordlists were presented to the participants with the words being underlined. In the second condition (distractor), two words were presented simultaneously on screen, one above the other. One of these words was underlined. Participants were instructed to study only the underlined word and ignore the other. The third condition (counting) was identical to the baseline condition, except participants were instructed to count aloud, from 1 to 6, and repeat this procedure during the study phase. The fourth condition (distractor-and-counting) included two words being presented as in the distractor condition and the participants were requested to count such as in the counting condition. Immediately after each list, recognition trials were conducted. During the recall phase, three words were presented simultaneously on the screen, one above the other, numbered 1 to 3. For the baseline and counting conditions, one of the words was the target word; two were not. For the distractor condition and the distractor and counting condition, one word was the underlined target word, one was the to-be-ignored from the same trial, and the third word was a new word. Again, they found that age group significantly impaired the maximum level of performance attainable and the slope toward that maximum performance. They concluded that for free and cued recall and in recognition, aging significantly impaired both the maximum level of performance attainable and the rate at which this is reached. Both above studies have shown that age group was significantly related to deficits in single-item episodic memory.

For associative memory, numerous studies have found that declines are more severe than single-item episodic memory declines (Buchler & Reder, 2007; Craik, 1983, 1986; Healy et al., 2005; Old & Naveh-Benjamin, 2008). In a meta-analysis completed by Old and Naveh-Benjamin (2008), they examined ARCD on both single-item and associative episodic memory with data from 90 studies. Their meta-analysis included 3,197 young and 3,192 older adults. Their results provided strong support for an age-related associative/binding deficit. This means that aging has a larger effect on memory for associative information than for item information. They also found an age-related associative deficit in memory for source, context, temporal order, spatial location, and item pairings for both verbal and nonverbal forms of memory. Ultimately, they found that there were age-related declines in episodic memory across a wide variety of experimental methods for both single-item and associative memory, but associative memory was more severely impacted by aging.

With strong meta-analytic evidence showing that aging has a significant impact on associative memory, the question is how does aging disproportionally impact associative episodic memory and not single-item episodic memory. A study that examined how aging impacts various aspects of associative memory was conducted by Healy et al. (2005) who conducted 3 experiments to examine how aging impacts participants' ability to recall unrelated word pairs and associative recognition of these pairs. During these 3 experiments, a group of young adults and a group of older adults would undergo testing that included studying word-pairs and completing an associative recognition task. The associative memory task consisted of seven test blocks. Each study list contained 48 word pairs. Across these 3 experiments they found that older adults had poorer associative recognition than the young adults. They also concluded that the declines in associative recognition are not as simple as declines in older adults' ability to recall information and that their ability to recognize items as familiar might also be impacted.

Executive functioning

In addition to age-related episodic memory deficits, researchers have examined how aging impacts executive functioning (Brennan et al., 1997; Crawford et al., Fjell et al., 2017; 2000; Grieve et al., 2007; Mejia et al., 1998). Executive functioning is an umbrella term for a set of cognitive processes (e.g., planning, monitoring, activating, switching, and inhibiting) that are necessary for the cognitive control of behavior such as: selecting and successfully monitoring behaviors that facilitate the attainment of chosen goals. Multiple studies have shown that there are age-related deficits on varying aspects of executive functioning (Brennan et al., 1997; Crawford et al., 2000; Fjell et al., 2017; Grieve et al., 2007; Mejia et al., 1998). A study that gives a good example of this was conducted by Fjell et al. (2017). They followed 119 young and middle-aged (23–52 years) and older (63–86 years) adults for 3.3 years with multiple assessments of both structural and functional brain connectivity, executive function, and processing speed via the Stroop task. They found that there were age-related reductions in inhibition that were greater than reductions in processing speed. In addition, they also found that, 82.5% of the age-related decline in executive function could be explained by changes in brain connectivity over time. This indicated that structural connectivity change in white matter tracts could explain age-specific declines in executive functioning.

This next study examined the same topic of aging and executive functioning (Brennan et al., 1997). Brennan et al. (1997) sought to investigate how aging influences Tower of Hanoi performance. Their study included three age groups (young adult, young elderly, or older elderly) to better understand how different stages of aging impact cognitive functioning. Their participants consisted of 19 elderly men and women broken up by age group into 9 young elderly with an average age of 65 years and 10 older elderly with an average age of 75 years. The young adult group consisted of 2 men and 10 women with an average age of 19 years. Their results showed that there was similar executive function performance for the 3-disc portion of the task for the young adults and the young elderly adults compared to the older elderly adults. During the 4-disk portion of the task where difficulty increased because of the addition of another disk and more move sequences, young adult had significantly better performance than both the young elderly and older elderly participants. Ultimately, their findings are consistent with previous work showing that aging results in significantly worse executive functioning capabilities.

Crawford et al. (2002) conducted a study to investigate if aging is related to a differential deficit in executive function, compared to deficits in general cognitive abilities (Wechsler Adult Intelligence Scale-Revised performance). This was completed across 2 studies. In Study 1 participants consisted of 123 individuals between 18 and 75 years old. All participants completed a battery of tasks assessing general cognitive ability, executive function, and memory. There was no evidence of a differential decline in executive function. This indicates that executive function is not more severely impaired by aging than general cognitive abilities are. Despite that, they did show that increasing age was related to significant declines on some of their measures of executive function. These measures included the modified card sorting task, the Stroop Test, and the Tower of London. Study 2 consisted of 90 participants between the ages of 60 and 89 years old. Again, these participants completed a battery of tasks assessing general cognitive ability, executive function, and memory. The results of the second study indicated a differential decline in one indicator of executive function, the Modified Card Sorting Test relative to age. This means that there were declines in the older adults' ability to perform this task that were over and above the declines found in general cognitive ability. They concluded that there are age-related declines in executive function, and some evidence of a differential decline on modified card sorting task performance compared to the age-related declines in general cognitive ability.

Across these studies, ARCD was found using a variety of cognitive measures including: the trail making task, clock in a box task, modified card sorting task, Stroop color word task, tower of Hanoi, and the executive maze task. With the numerous studies showing ARCD in episodic memory and executive functioning, behavioral interventions are necessary to provide protective effects against ARCD.

Cognitive reserve hypothesis

The cognitive reserve hypothesis initially included two types of reserves that were cognitive and brain (Stern, 2002). Individuals' brain reserves encompassed the brain structures, and it was suggested that individuals with greater brain volume would be better inclined to stave off the onset of cognitive deficits (Katzman, 2012). This was expected to happen through more efficient neural networks delaying the manifestation of these deficits (Katzman, 2012). Satz (1993) previously suggested that these brain reserves would eventually reach a critical point, where the greater brain volume one individual might have compared to another would no longer compensate for aging and cognitive deficits would be evident. The cognitive reserve hypothesis is a flexible model that describes the relationship between brain volume and additional processing required by individuals to compensate. With decreases in brain volume, individuals who want to overcome this theoretically need to compensate with increased processing of information potentially via other brain regions or greater activation (Stern, 2002). A common example of this would be an individual who has severe atrophy of brain volume in various regions but shows no signs of cognitive deficits at that point. This would be an example of someone compensating for a lack of brain reserves with additional processing via other brain regions or greater activation in the atrophied regions.

The cognitive reserve hypothesis suggests that intelligence, educational or occupational attainments, and cognitively stimulating activities may build up cognitive reserves that allow some individuals to cope with ARCD better than others (Opdebeeck et al., 2016; Scarmeas & Stern, 2003). It is suggested that various aspects of life experience can result in more efficient cognitive networks and therefore build up a cognitive reserve that delays the onset of clinical manifestations of cognitive decline (Scarmeas & Stern, 2003).

Previous research has found that higher levels of education and more complex occupations during middle-age were associated with a decrease in risk of cognitive impairment (Marioni et al., 2012). It has also been found that being socially engaged reduced the risk of going from being slightly impaired to moderately or severely impaired (Marioni et al., 2012). These studies have shown that attaining greater education, having cognitively stimulating jobs, and being socially engaged all help to decrease the odds of cognitive deficits or more severe cognitive deficits. Related to the current study, physical activity engagement has been suggested in the model of cognitive reserves as low physical activity levels are associated with a higher risk for dementia and, greater levels of physical activity engagement have been shown to be positively related to greater total brain and hippocampal volumes (Tan et al., 2017).

More recently, an updated cognitive reserve hypothesis has been proposed (Stern, 2009). The updated cognitive reserve hypothesis includes two major components, neural compensation, and neural reserves (Stern, 2009). These interact with one another and influence cognitive processing as we age into older adulthood. Neural reserves are an individuals' variability in neural efficiency, capacity, and flexibility within brain networks that is needed for cognitive processing in the healthy brain. Neural efficiency refers to less activation in the brain with an equal or superior performance behaviorally. Capacity refers to greater levels of activation with superior performance behaviorally. Flexibility would refer to an individual using alternate strategies to compensate behaviorally. Based on the cognitive reserve hypothesis, it would be suggested that individuals with greater processing capabilities in any of the three domains would be able to cope with brain pathology more so than those with less neural reserves and therefore would not show cognitive deficits on behavioral tasks. Neural compensation is like neural reserves, but it is specific to the structure of the brain unlike neural reserves which focuses on the function or use. With a loss in brain volume with aging, to maintain performance, individuals need to compensate by using other brain structures or networks that are not normally used on a specific task in a healthy brain.

The effects of exercise on cognitive functioning

Acute exercise - cognition

A large body of research has been conducted examining the effects of a single bout of aerobic exercise on varying types of memory (Chang et al., 2019; Chang et al., 2011; Coles, & Tomporowski, 2008; Etnier et al., 2021; Etnier et al., 2016; Hötting et al., 2016; Labban, & Etnier, 2011; Labban, & Etnier, 2018; Netz et al., 2007; Pesce et al., 2009; Segal et al., 2012; Sng et al., 2018) and executive functioning (Barella et al., 2010; Byun et al., 2014; Peiffer et al., 2015; Slusher et al., 2018; Weng et al., 2015). Meta-analyses have found that single bouts of aerobic exercise enhance both memory and executive functioning in various populations (Chang et al., 2012; Etnier et al., 1997; Roig et al., 2013).

In the meta-analysis completed by Chang et al. (2012), they included multiple aspects of cognition but also examined cognitive domain as a moderator of the effects that acute exercise has on cognition. For executive functioning, they found that immediately following an exercise bout, effects for executive functioning (Cohen's d = 0.189), attention (Cohen's d = 0.416), and crystalized intelligence (Cohen's d = 0.271), all had significantly larger effects than other cognitive domains. Following a delay after the exercise bout, they found that executive functioning (Cohen's d = 0.171) and crystallized intelligence (Cohen's d = 0.275) had the largest effects of all the cognitive domains. When they also examined age as a potential moderator, they found that older adults (Cohen's d = 0.181) and high school age adolescents (Cohen's d = 0.165) had the largest effects compared to young adults and elementary age children who both still had effects significantly different than zero. The age moderating effects were for all cognitive domains though and not executive functioning specifically.

In a meta-analysis completed by Roig et al. (2013), they found that acute exercise has small-to-moderate (SMD = 0.26) effects on short-term memory (STM) and moderate-to-large (SMD = 0.52) effects on long-term memory (LTM). These results suggest that a single bout of exercise has its greatest benefits for memory when retention tests are performed long after encoding. They also found that young adults showed greater improvements in short and long-term memory following acute exercise compared to older adults. However, the SMD of these analyses were calculated with data from a small number of studies (n = 3) utilizing older adults and should be interpreted with caution. Despite the promising findings to date, very few acute exercise studies have examined the population most vulnerable to ARCD which is older adults (ages 60+ years old). This is surprising given that the cognitive reserve hypothesis suggests that older adults could achieve greater benefits from cognitively stimulating activities such as exercise than other age groups (Scarmeas & Stern, 2003; Tan et al., 2017). These acute benefits on cognition could be achieved through changes in neural activation which has been previously shown to occur following an acute bout of aerobic exercise (Slutsky-Ganesh, et al., 2020).

To my knowledge only a handful of studies have examined how a single bout of aerobic exercise effects executive functioning (Alves et al., 2012; Barella et al., 2010; Chang et al., 2019; Peiffer et al., 2015) and episodic memory (Etnier et al., 2021; Schramke, & Bauer, 1997; Segal et al., 2012; Netz et al., 2007) in older samples. The current study will extend on this work by examining both young and older adults to better understand the effect of age group on cognitive functioning following an acute bout of aerobic exercise. In a previous study, Etnier et al. (2021) found that 20-min of moderate to vigorous aerobic exercise (55 to 65% heart rate reserve) prior to memory encoding yielded significant STM and LTM improvements for middle age to older adults (50 to 75 years old) compared to a control condition. Segal et al. (2012) found that short-duration vigorous-intensity exercise enhanced visual memory in both mildly cognitive impaired older adults (M = 71.4 years) and in healthy controls (M = 69 years). Despite those findings, Schramke and Bauer (1997) found no benefits for walking on STM on a word list paradigm for older adults (60-80 years), and Netz et al. (2007) found no differences between a control group and two exercise groups (60% of HRR and 70% of HRR for 44 mins) on Digit Span Forward (STM) performance by late middle-aged men and women (50 – 64 years). Overall, studies testing the potential role of acute exercise in terms of memory enhancement for older adults have yielded mixed findings.

When examining the studies on executive functioning for older adults, Barella et al. (2010) invited participants (adults ages 60 – 90 years) to complete a Stroop task at 12 time points following 20-mins of walking and found that there were significant improvements immediately following exercise on the color portion of the task but not on the Stroop interference scores. Alves et al. (2012) asked 42 healthy women (M = 52.0 years) to complete three counter balanced visits of either aerobic exercise (30 min of walking at 50–60% HR reserve), strength exercise (two sets of 15 maximal repetitions for six exercises: chest press, leg press, lat pull-down, leg extension, squat, and sit-ups), or a control condition (15 min of instructions about the benefits of regular exercise training on overall health followed by 15 min of low intensity active stretching) followed by the Stroop task and the Trail Making task. Following both the aerobic and strength exercise visits, they found that the time to complete the Stroop non-color word and color-word portions were significantly decreased compared to the control, but Trail Making task performance was unchanged. In a study completed by Peiffer et al. (2015), 11 healthy females (60 – 75 years) completed 20-min aerobic exercise bouts at 50% and 75% of VO_2 max. Participants completed a modified flanker task and a d2 task of sustained attention before, immediately following exercise, and 30-mins post-exercise. They found that flanker reaction time scores and d2 performance were improved following both exercise bouts, but they did not have a control condition and were comparing pre to post changes. Chang et al. (2019) asked 40 late middle-aged (M = 57.58 years) volunteers to complete four counter-balanced visits consisting of moderate to vigorous cycling (60 – 70% HRR) for 10, 20, or 45-mins and a control condition. They assessed inhibition via the Stroop task. Their participants had significantly reduced response times for both congruent and neutral conditions on the Stroop task following 20-mins of exercise compared to the control condition and the 10-min bout. The 20-min bout also resulted in significantly shorter response time on the incongruent trials than all other conditions. Despite the promising findings above, only two out of the four studies were conducted on older adults.

Most studies examining the acute exercise – cognition relationship have been conducted on a readily available population of college students that are traditionally healthy and physically active. Without more empirical evidence, it would be premature to assume that older adults will respond in the same manner cognitively that healthy young adults would. This gap in our field creates a need to further research the impact that aging has on the exercise – cognition relationship. Traditionally in Kinesiology, researchers who are interested in aging study older adults to see how they respond to single bouts of exercise or chronic engagement. While this adds valuable information, it is not truly allowing researchers to examine the effects of aging.

Researchers in the field of cognitive psychology commonly use methods to examine how aging impacts cognition and that is by directly comparing groups of young and older adults in a single study using the same methods. While there are other more robust designs such as a cross-lagged panel design or a longitudinal design, these methods require much more time in terms of years to examine the effects of aging. By using a cross-sectional design with two age groups it allows us to examine the effects of aging at one time point and gives us a valid starting point before utilizing more robust designs in the future. While meta-analyses allow us to compare effect sizes across age groups, they do not allow us to directly compare these two groups using the exact same methods and procedures. If exercise can be used as a behavioral strategy to slow down the rate of ARCD, we need to first understand the differences between young and older adults' acute responses to exercise to allow us to understand if the large body of work done on young adults can be translated to older adults. With a greater understanding as to how aging impacts the exercise – cognition relationship in terms of acute changes, we can then use that knowledge to build more effective and robust interventions to examine the impact that chronic exercise can have.

Chronic exercise – cognition

In addition to the burgeoning literature that has examined how an acute bout of aerobic exercise effects cognitive functioning, a large body of work has been done examining how chronic exercise or physical activity engagement influences cognitive functioning. While numerous studies have been conducted over the last two decades examining how a single bout of aerobic exercise impacts cognitive functioning, to better understand how to best prescribe exercise for cognitive benefits the long-term effects must be further examined. In a meta-analysis completed by Etnier et al. (1997), they examined 134 studies looking at multiple aspects of cognition that were identified as cross-sectional, acute exercise, or chronic exercise designs.

They found that across the three designs, an overall effect size of 0.25, suggested that exercise has a small positive effect on cognition. Their results also indicated that significantly larger effect sizes were found when studies utilized cross-sectional designs (M = 0.53, ES n = 117) than were found for both chronic exercise designs (M = 0.33, ES n = 358) or acute designs (M = 0.16, ES n = 371). They also found that studies utilizing chronic exercise treatments showed significantly larger effect sizes than those using acute bouts of exercise. Despite their promising findings, they do list a few weaknesses that readers should account for when interpreting their results. One weakness was that conclusions from the cross-sectional studies are limited in terms of the inability to presume causation. Individuals who are more physically fit or engage in more exercise behaviors might not have better cognitive functioning because of the engagement in those activities but instead because their performance could reflect pre-exercise differences that already occurred between them and less active individuals.

Another meta-analysis that examined how chronic exercise was related to cognitive functioning in older adults was completed by Colcombe and Kramer (2003). They included 18 intervention studies where participants were randomly assigned to groups and completed some type of aerobic fitness training. Their results showed that training had a robust but selective effect on cognition (hedges $g = 0.478$, $p < .01$), with the largest benefits occurring for executive-control processes (hedges g = 0.68, $p < .05$). These effects were moderated by the length of the training intervention, with longer duration programs having the largest effects (hedges g = 0.674), the type of exercise training being completed, with a combination of aerobic and resistance exercise having a larger effect than aerobic alone (0.59 vs 0.41), and the duration of individual training sessions with moderate length sessions (31 – 45 mins) having significantly larger effects than short (15 – 30 mins) or longer (46 – 60 mins) sessions (moderate: 0.614, long: 0.466, and short: 0.176). They concluded that fitness training improved cognitive performance 0.5 SD across all types of cognitive domains. They also concluded that while this meta-analysis added valuable information regarding exercise training and cognition that their moderator analyses did show that other variables need to be accounted for in future research.

A meta-analysis that specifically examined the relationship between memory and chronic exercise engagement was conducted by Roig et al. (2013). Their meta-analysis included 21 studies examining chronic cardiovascular interventions. Results showed that chronic exercise had small (SMD = 0.15; p = 0.02; N = 37) effects on short-term memory and insignificant effects (SMD = 0.07; 0.26; p = 0.51; N = 22) on long-term memory. Importantly, they also examined age as a potential moderator and found that young adults showed greater improvements in short-term memory following chronic exercise engagement. But this conclusion should be interpreted with caution as the SMD for these analyses was calculated with data from a small number of studies. In their conclusions, they argued that chronic exercise has negligible effects on memory but provides the necessary stimuli to prepare individuals for memory processing. While these two meta-analyses give valuable insight into the relationship between exercise engagement and cognitive functioning there are still substantial gaps in our understanding. Does the cognitive domain being examined moderate the effects of chronic exercise such that memory is less impacted than other types or have there not been enough studies capable of completing long-term exercise interventions on various groups to give enough evidence to make this conclusion. The current study seeks to examine how chronic exercise engagement is related to cognitive functioning across multiple cognitive domains to better understand if the neuroprotective effect of exercise is specific to certain cognitive abilities.

Proposed mechanisms for the exercise – cognition relationship

Even though this dissertation is not specifically designed to examine mechanisms for the exercise – cognition relationship, it is valuable to discuss the putative mechanisms. As stated before, aging is associated with cognitive declines and these declines are associated with decreased gray matter volume both cross-sectionally (Erickson et al., 2010; Ramanoël et al., 2018; Zimmerman et al., 2006;) and longitudinally (Gorbach et al., 2017; Kramer & Erickson, 2007). Given the general atrophy that occurs in the brain with aging, it is important to better understand what health behaviors have a positive influence on gray matter volume and could potentially slow down the rate of age-related declines in brain structure and cognitive function. Brain derived neurotrophic factor (BDNF) is a protein that is associated with gray matter volume (Erickson et al., 2010; Hashimoto et al., 2016). With aging, BDNF levels decrease. Despite that, promising work has shown that increased levels of BDNF for older adults is associated with positive outcomes for both brain structure (Erickson et al., 2011), executive function (Leckie et al., 2014), and episodic memory (Ward et al., 2014).

Following exercise, BDNF in rodents has been shown to increase within the hippocampus (Berchtold et al., 2001), the prefrontal cortex (Geng et al., 2013) and the amygdala (Liu et al., 2009). This may suggest that exercise affects hippocampal-dependent cognition (e.g. memory) and executive functioning through BDNF. There is some empirical support for the response of BDNF following exercise in humans to be associated with improved executive function. Hwang et al. (2016) investigated the effects of high-intensity acute exercise on BDNF and executive function in young adults. Following exercise there were significant increases in BDNF and improvements in inhibitory control and set shifting. Further, the increase in BDNF from pre- to post-exercise was associated with the improvement in set shifting. Despite the promising evidence to date, more work is needed to fully understand the relationship.

There is sufficient evidence to suggest that BDNF is associated with synaptic plasticity, as well as neuroprotection and neurogenesis (Marosi & Mattson, 2014), therefore, increasing BDNF in older adulthood may counter some age-related changes in the brain and prevent declines in cognitive function. A meta-analysis completed by Dinoff et al. (2017) included 55 studies examining changes in BDNF following single bouts of exercise in healthy adults. They found that there was a significant increase in peripheral BDNF following acute exercise bouts. Their results indicate that across the 55 studies the ones that utilized males had a significant increase in BDNF following acute exercise, but females did not. Other important findings were that the duration of the exercise should be at least 30 minutes and there may be a higher response in individuals with higher levels of fitness. Dinoff et al. (2017) results show an acute bout of aerobic exercise can cause a peripheral increase in BDNF which is promising for BDNF as a mechanism to the exercise – cognition relationship.

In a systematic review, de Melo Coelho et al. (2013) examined whether BDNF increased both acutely and chronically with exercise engagement in older adults (65+ years old). In their search regarding chronic exercise and BDNF changes in the elderly they found 6 articles out of which 5 found significantly increased BDNF following either aerobic exercise engagement or a combination of aerobic and strength training-based exercise. Ultimately due to the low number of studies they found examining this relationship they could not make strong conclusions regarding the type or intensity of exercise needed to result in these changes but did suggest that moderate intensity exercise seems to be the most effective in causing increases in peripheral BDNF levels.

Despite the evidence that single bouts of aerobic exercise result in significantly increased release of BDNF (Dinoff et al. 2017), that chronic exercise engagement appears to cause an increase in peripheral BDNF levels (de Melo Coelho et al., 2013), and that chronic aerobic and resistance exercise result in significant improvements in cognitive functioning (Etnier et al., 1997; Roig et al., 2013), the relationship between the two has still not been definitively shown across multiple studies. While it's simpler to conclude that since both are occurring following exercise, BDNF must be the mechanism for the exercise-cognition relationship, we should not assume that because both are co-occurring in close temporal proximity to exercise bouts that they are directly related. More research is needed to fully understand how BDNF and cognitive changes occurring related to exercise are intertwined.

While increased levels of BDNF is a highly studied mechanism for the exercise – cognition relationship, there are other mechanisms that have been studied more recently. In a review by Moriarty et al. (2019) they examined a variety of potential mechanisms including BDNF and lactate release. In their search of studies related to the topic they found studies linking a relationship between lactate release and the expression of BDNF (Newman et al., 2011; Yang et al., 2014). In rats they also found that lactate injections could alleviate cognitive impairments that resulted from traumatic brain injuries (Holloway et al., 2007). Lactate is a biproduct given off during exercise. The potential link between lactate release and BDNF expression is a quite important one if we want to find a link between chronic exercise engagement, BDNF, and cognitive functioning. Other important animal research has found that the blocking of BDNF expression in mice impaired long-term potentiation in the brain (Korte et al., 1996). Long-term potentiation involves persistent strengthening of synapses that lead to a longer lasting increase in signal transmission between neurons and could result in more efficient processing of information.

Purpose

The purpose of this project was to better understand the impact aging has on the exercise – cognition relationship. The current study was a hybrid design with two concurrently conducted studies. Study 1 was a cross-sectional design to examine how subjectively measured physical activity level is related to cognitive functioning and how aging moderates this relationship. Study 2 was a mixed design with participants engaging in both an acute exercise visit and a control visit to examine how a single bout of aerobic exercise impacts cognitive functioning and how aging moderates that relationship.

CHAPTER II: STUDY 1

Abstract Study 1

A large body of research has shown that chronic physical activity engagement benefits varying aspects of cognitive functioning. Despite that, the effects that aging has on this relationship have not been extensively studied. This study investigated the relationship between physical activity engagement and cognitive functioning and the extent to which that relationship might be moderated by age group. Using a cross-sectional design, participants came to the lab for one visit and completed the Global Physical Activity Questionnaire (GPAQ), demographics, a healthy history questionnaire, and a battery of cognitive tasks assessing episodic memory, executive functioning, working memory, and associative memory. Participants consisted of both sedentary and physically active young (20 – 30 years) and older adults (60 – 70 years). Hierarchical multiple regression analyses were completed to examine the relationship that physical activity level, age group, the interaction of age group by physical activity level, and other demographics have with cognitive functioning. Our results indicated that for both memory and executive functioning, age group had a significant negative relationship with performance. We also found that for both young and older adults select aspects of memory were positively related to engagement in physical activity (long-term memory, associative memory). We did not find strong evidence that older adults had a stronger relationship between their physical activity engagement and cognitive functioning compared to young adults. These findings could suggest that, throughout the adult lifespan, engagement in physical activity is beneficial for memory performance and could be utilized as a behavioral treatment to potentially slow down the rate of ARCD. In conclusion, it appears both young and older adults stand to gain memory benefits from physical activity engagement while executive functioning is not significantly affected.

Introduction Study 1

Numerous studies have examined how physical activity or exercise engagement impact cognitive functioning (Chang et al., 2012; Etnier et al., 1997; Roig et al., 2013). Across these studies there are traditionally three designs that have been utilized to better understand the exercise – cognition relationship. One is how a single bout of exercise impacts cognition acutely either immediately following that bout or following a longer delay (hours to days later). Another design is examining how chronic engagement in exercise impacts cognition through a randomized control trial or quasi-experimental design. In randomized control trials participants are randomly assigned to be in an exercise intervention group or a control group while in a quasi-experimental design participants are not randomly assigned but rather are assigned to all be in an exercise intervention group or assigned to groups based off predetermined guidelines or participant choice. In the exercise group, participants will usually engage in a certain intensity of exercise for several months under some type of supervision. The third design is examining how a participant's physical activity level measured either subjectively (questionnaires) or device based (pedometers or accelerometers) is related to their cognitive functioning. The third design allows researchers to examine the relationship between physical activity engagement and cognitive functioning without following the participants for months or years and requiring them to come back in for testing multiple times. The current study utilizes a cross-sectional design to examine how subjective physical activity level is related to cognitive functioning with respect to aging.

A meta-analysis conducted by Etnier et al. (1997) found that studies utilizing a cross-sectional design (M = 0.53, SD = 0.77) showed significantly larger effect sizes than both chronic exercise studies (M = 0.33, SD = 0.58) and acute exercise studies (M = 0.16, SD = 0.60). In an exercise intervention, participants will normally go from being sedentary to engaging in exercise for a few months to a year. These larger effects may be because cross-sectional studies compare participants who could have been engaging in physical activity or exercise for multiple years and built up greater cognitive reserves from doing so resulting in a greater difference between them and someone of the same age who has been sedentary.

While there is a large body of research showing that exercise has numerous health benefits, the number of people currently reported to meet the guidelines is low. Currently, only 34% of adults ages 18 to 24 years old meet the physical activity guidelines for aerobic and muscle strengthening activities (National Center for Health Statistics, 2017). Even more alarming, only 16.4% of adults ages 65 to 74 years old meet those guidelines. As individuals age, Americans become less physically active but in addition to that, the types of activities they participate in change (National Center for Health Statistics, 2017). We would not presume that older adults are engaging in the same type of activities that young adults do because of safety, access, or preference. Due to this, the types of activities older adults engage in need to be considered such as occupational and domestic activities performed throughout one's day. For example, while older adults might not be engaging in resistance exercise like young adults, they could be active in terms of gardening or household duties that require them to be active to complete their tasks. These types of activities need to be accounted for instead of just the traditional recreational activities that many think of as exercise.

In a meta-analysis, Sofi et al. (2011) examined prospective studies that investigated the association between physical activity and the risk of cognitive decline in nondemented participants. They included 15 prospective studies in their final analyses. They found that participants who performed a high level of physical activity were significantly protected against cognitive decline during the follow-up visit. Even more interesting, they found that even low-to-moderate levels of exercise had a significant protective effect against cognitive impairment. While these findings are highly valuable, a prospective study takes years to complete, and work completed to date has used generally poor measures of physical activity behavior and have not sought to examine the variation there might be across different cognitive domains.

There are numerous cross-sectional studies that have examined how physical activity levels are related to cognitive functioning (Boucard et al., 2012; Falck et al., 2017; Hayes et al., 2015; Ruiz et al., 2010; Sibley & Etnier, 2003; Quan et al., 2018). Despite that, only a few of them have done so using a sample of non-clinical, healthy older adults or with the goal to examine how aging impacts this relationship (Boucard et al., 2012; Falck et al., 2017; Hayes et al., 2015). Hayes et al. (2015) found that older adults performed more poorly on tasks of executive function and episodic memory compared to young adults. They also found that physical activity was positively associated with a composite measure of visual episodic memory and face-name memory accuracy in older adults but not associated in the young adults.

Boucard et al. (2012) examined how physical activity level and fitness were related to executive functioning in a group of young adults (18 – 28 years old), young-old adults (60 – 70 years old), and old adults (71 – 81 years old). They found that physical activity level was positively related to older adults' inhibition but no other aspects of executive functioning and not significantly related in the young adults or the young-old adults. Falck et al. (2017) examined the differences in physical activity and sedentary behaviors in individuals with probable MCI and without, and how those behaviors were related to cognitive functioning across these two groups. They found that participants with probable MCI were less active and more sedentary than those without MCI. They also found that greater levels of physical activity were positively associated with greater cognitive functioning in participants without MCI but not with probable MCI. It is possible individuals with probable MCI have experienced severe enough cognitive deficits that physical activity engagement does not have a noticeable impact or that the lack of activity in this group resulted in an inability to examine how physical activity is truly related to their functioning. Across these three studies the consistent findings were that physical activity level was positively associated with cognitive functioning in the older adults (Boucard et al., 2012; Falck et al., 2017; Hayes et al., 2015;) but not in the young adults (Boucard et al., 2012; Hayes et al., 2015), A potential explanation could be that the young adults have not begun to experience ARCD and therefore physical activity engagement does not impact their cognitive functioning as strongly. For the older adults, this could occur because of greater buildup of older adults' cognitive reserves through more chronic engagement in physical activity compared to those who are more sedentary.

Despite the plethora of research examining the relationship between physical activity engagement and cognitive functioning, very little has been done with respect to aging. To better understand the moderating effects of aging, the current study replicates the design used by Hayes et al. (2015) and extends their previous work by utilizing an associative memory word-list paradigm that has been shown to be more severely impacted by the effects of aging over the experimental face-name task utilized by Hayes et al. (2015). The purposes of Study 1 are: 1) to examine if a sample of healthy, cognitively normal older and younger adults have significant differences in their cognitive abilities at baseline, and 2) examine if physically active level is related to episodic memory, associative memory, inhibitory control, and spatial working memory performance, and moderated by age group. Based off previous research, the hypotheses for study 1 are that 1) older adults will perform significantly worse than younger adults on the cognitive tasks and 2) that age group will moderate the relationship between physical activity level and cognitive functioning such that older adults who are more physically active will perform significantly better on the cognitive tasks than those who are less active, and this relationship will be weaker in the young adult group.

Methods Study 1

Study design

A cross-sectional design was used with two age groups (young and older adults) visiting the laboratory once. Participants were instructed not to exercise 24 hours prior to coming into the lab and to not ingest caffeine for 2 hours prior to their visit which was confirmed when participants arrived for testing. See table 1 for study procedures.

Participants

Participants were recruited by use of flyers, at gyms, wellness centers, fitness classes, and senior centers in the Greensboro area and at the University of North Carolina at Greensboro. The inclusion criteria were: 20 to 30 (young adult group) and 60 to 70 (older adult group) years old, no presence of cognitive impairment as assessed by the Montreal Cognitive Assessment (MOCA), and no clinical conditions that could impact physical activity engagement or cognitive functioning (Assessed via ACSM Health Screening form). Using the effect size (f^2= 0.40 from associative memory) from the omnibus tests in Hayes et al. (2015) with α=0.05 and power=0.80, the total sample size required to detect a significant interaction effect using a multiple regression was estimated to be N = 23 (GPower 3.1.9.4). While the current study is utilizing similar methods to the Hayes et al. (2015) study, previous meta-analyses have shown that exercise has small to moderate sized effects on episodic memory (Roig et al., 2013). To ensure the study is fully powered a medium effect size (f^2= 0.15) with α=0.05 and power=0.80 was used demonstrating that 53 participants were needed. Participants consisted of n = 54 adults (n = 28 young adults, n = 26 older adults) with an average age of 23.29 years for the young adults and 66.15 years for the older adults. See table 2 for participants' demographic information and table 3 for participants ethnicity information.

Table 1. Study 1 procedures

Informed Consent
Questionnaires
RAVLT Trials 1 – 7
Stroop Task
Spatial working memory task
Rey Auditory Verbal Learning task delayed recall and recognition (following 20 min delay)
Paired-Associate memory task
20-min delay (educational video)
Paired-Associate Delayed Recall

Procedures

Participants who met the inclusion criteria were scheduled for their lab visit. During their visit participants read and signed an informed consent form approved by the UNCG Institutional review board, filled out a demographic questionnaire (age, sex, educational level) and the Global Physical Activity Questionnaire (GPAQ), and completed the MOCA. Height and weight were measured using a two-in-one stadiometer and scale with participants' shoes on. Next participants completed a battery of cognitive tasks assessing episodic memory and executive function (See table 1 for ordering of cognitive battery).

Measures

Cognitive status. To ensure that participants showed no presence of cognitive impairment, participants completed the MOCA. Scores on the MOCA range from 0 to 30, and individuals who received a score of 26 or higher were considered to have no cognitive impairment and allowed to participate (Smith et al., 2007). The MOCA has high test-retest reliability (correlation coefficient=0.92, p<.001), internal consistency (Cronbach alpha=0.83), and high validity when compared to the Mini Mental State Exam (r=0.87, p<.001; Nasreddine et al., 2005).

Physical activity level. The Global Physical Activity Questionnaire (GPAQ) was used to measure participants' physical activity level. The GPAQ is a self-report measure of physical activity that was selected because it is a reliable and a valid self-report measure of physical activity for adults ages 18-75 years old, thus spanning the entire age range of both groups being recruited for this study. The GPAQ was completed with the participants in a semi-interview style to ensure that participants were not confused as to the different intensities that various types of exercise might fall under and to ensure accurate reporting as to the number of minutes they were engaging in these activities. The GPAQ was created by the World Health Organization and consists of 19-items that assess time spent performing moderate and vigorous intensity physical activity for three domains (work, travel, and recreational activities), as well as time spent engaging in sedentary behavior during a typical week (Bull et al., 2009). Physical activity data collected from the GPAQ was used to calculate an individual's metabolic equivalent minutes per week (MET-mins/week). Reliability of the GPAQ is moderate to strong (K = 0.67 to 0.73) across the three domains of physical activity. Concurrent validity assessed by comparing the GPAQ to the International Physical Activity Questionnaire-short form (Lee et al., 2011), is moderate with

Spearman's rho coefficients ranging from 0.45 for moderate physical activity, 0.57 for vigorous physical activity, and 0.65 for sedentary behavior. In addition, the criterion validity of the GPAQ, which has been assessed by examining the association between GPAQ MET-mins/week and pedometers and accelerometers, is comparable to other self-report measures of physical activity with Spearman's rho coefficients ranging from 0.06 to 0.35 (Bull et al., 2009).

National Institutes of Health Toolbox questionnaires. The NIH Toolbox was developed through a collaborative, multi-institutional (256 scientists and staff at over 80 institutions) initiative to develop state-of-the-science tools to measure important neurological and behavioral indicators of cognitive, motor, emotional, and sensory health from ages 3-85. The NIH Toolbox measures have been widely validated to assess various aspects of social well-being and the current study included measures of emotional support, instrumental support, friendship, loneliness, and perceived stress (Cyranowski et al., 2013; Salsman et al., 2013; Salsman et al., 2014). Participants completed the five NIH Toolbox questionnaires assessing emotional support, instrumental support, friendship, loneliness, and perceived stress to be utilized as potential covariates.

Verbal single-item learning and memory. This was assessed using the Rey Auditory Verbal Learning task (RAVLT) (Majdan et al., 1996; Schmidt, 1996; Taylor, 1959) which is a word list memory task consisting of two lists of 15 words. The RAVLT has been validated for various age groups including young adults 18 years of age or older and adults over 50 years of age (de Sousa Magalhães et al., 2012; Rosenberg et al., 1984; Vakil & Blachstein, 1997). Prior to playing the wordlists, the volume was adjusted until the recording could be clearly heard by the participant. After hearing a wordlist, participants were instructed to repeat as many of the words as they remembered in thirty seconds. It was made clear that the order of their responses did not matter. After the 15 words were read by the recording the participants were prompted to name as many words as they could remember. This process of list exposure and immediate recall was repeated four additional times for List A (Trials 2 - 5). After the fifth trial, participants were told that they would now hear a different list, called “List B”. After hearing List B, they were asked to repeat as many of the words from List B as possible in 30 seconds (Trial 6). Following Trial 6, and without hearing List A again, participants were asked to repeat as many words from List A as they could remember (Trial 7). Trial 1 is considered a measure of STM. Change in performance across Trials 1-5 was interpreted as an indication of learning. Trial 6 is an interference trial designed to prevent participants from continuing to practice the items from List A. Performance on Trial 7 was considered a measure of long-term memory (LTM - immediate) after a brief delay of less than two minutes. Researchers’ audio recorded participants’ responses during the RAVLT to ensure accurate scoring of responses.

LTM following a longer delay was assessed 20-mins later. The primary outcome was a free recall measure. Participants were asked to recall as many words as they remembered from List A. Following this, participants read a list of words which consisted of words from List A, List B, and 20 new words (Majdan et al., 1996). Participants were asked to identify words as being from List A, List B, or a new word from neither list.

Verbal paired-associative memory. This was assessed using the VPA15 which was designed by Uttl et al. (2002). This task included eight word-pairs (four related and four unrelated) from the Wechsler memory scale/Wechsler memory scale-revised verbal paired associates subtest plus seven new unrelated word pairs. The VPA15 was administered according to the published instructions for the Wechsler memory scale-revised verbal paired associates test (Wechsler, 1987) with one exception. The word pairs and cue words were recorded and presented via speakers to allow for consistent presentation to all participants. This test was utilized due to potential ceiling effects when using the Weschler memory scale verbal paired associates test. Uttl et al. (2002) found that on trial 1, 13.4% of participants had scores greater than 8 words which would be the maximum possible with the Weschler memory scale. They also found that with the VPA15 only 1% of participants achieved perfects scores on trial 1 and only 14.5% of participants obtained a perfect score on trial 2. During visit 1, participants listened to an audio recording for each word pair at a rate of one word per second. Participants then heard the first word of each pair read with a short pause to allow them to respond verbally with the second word in the pair. During each trial, participants were informed if they were correct or incorrect. If they were incorrect the correct word was played for them via an audio recording. This allowed for greater encoding of the word pairs across the 3 trials. This process was completed for each word on trial 1 and then the same process was completed for trial 2. Participants then had a 20-min delay before they completed the recall process again for all 15-word pairs where they watched an educational video with closed captioning. Performance was assessed as the number of response words correctly recalled for trial 1, trial 2, and following the 20-min delay (LTM).

Executive function tasks. A computerized version of the classic color-word Stroop task was used to assess executive functioning (Bailey et al., 2012; Stroop, 1935). Previous research has shown high reliability for both latency (as: 0.96 – 0.98) and error rates (as: 0.61 – 0.79) indicating the measures are reliable over time (DiBonaventura et al., 2010). Participants were presented with words printed in an ink color that is either congruent (i.e., the word RED printed in red ink), neutral (i.e., the word CAR printed in red ink), or incongruent (i.e., the word RED printed in blue ink) to the word's meaning. Words were randomly presented for 2.5 seconds, and participants were instructed to respond as quickly as possible to indicate the inked color of the word. Participants respond by pressing a key on a standard keyboard with the index, middle, and ring fingers of their dominant hand. The test included 36 incongruent trials, 36 congruent trials, and 42 neutral trials. A series of 9 practice trials were completed before starting the task to acquaint the participant with the instructions. When the participant did not get at least 5/9 practice trials correct they were instructed to complete the practice again. Stimuli were presented using E-Prime 3.0 software (Psychology Software Tools, Inc., Pittsburgh, PA, USA). Interference scores were created by calculating a difference score between the incongruent and the congruent trials for both accuracy and reaction time. This variable was a measure of the interference effect of the Stroop task. Higher scores indicate a greater interference effect of having to inhibit the incongruent information being presented in comparison to the congruent trials where the information matches.

To assess spatial working memory as an aspect of executive function, a spatial working memory task was utilized (Erickson et al., 2011; Erickson et al., 2010; Erickson et al., 2009; Heo et al., 2010). Several practice trials were performed before each completion of the task to acquaint the participants with the task instructions and responses. During the task, a fixation crosshair appeared for 1 second, and participants were instructed to keep their eyes on the crosshair. After the fixation, one, two, or three black dots appeared at random locations on the screen for 500 ms. The dots disappeared from the display for 3 seconds. During that time, participants were instructed to try to remember the locations of the previously presented black dots. At the end of the three second delay, a red dot appeared on the screen in either one of the same locations as the original target black dots (match condition) or at a different location (nonmatch condition). Participants had two seconds to respond to the red dot by pressing one of two keys on the keyboard—the “x” key for a nonmatch trial and the “m” key for a match trial. Forty trials were presented for each set size (one, two, or three locations), with 20 trials as match trials and 20 trials as nonmatch trials that were randomly presented. Participants were instructed to respond as quickly and accurately as possible.

Statistical analyses

Alpha was set at 0.05 for all analyses. Preliminary analyses were performed to ensure there are no violations of the assumptions of normality, linearity, multicollinearity, and homoscedasticity. To examine the predictive relationship of sex, age group, education, PA level, and PA level X age group interactions on cognitive performance, hierarchical multiple regressions were conducted separately for each cognitive outcome measure. Continuous predictor variables (GPAQ; Met*mins/week and education) were centered at the mean. Additional predictor variables were examined and tested to increase the strength of the model (NIH toolbox variables, BMI), but were excluded due to lack of significant predictive ability or lack of any change to the overall model fit. Outcome variables that were assessed included: RAVLT trial 1 (STM), trial 7 (LTM) and trial 8 (delayed recall), Paired-Associates trial 1, trial 2 and delayed recall, Stroop interference scores for reaction time and for accuracy, and Spatial Working memory reaction time and accuracy scores for each of the three set sizes. Model 1 includes sex and education to control for these potential confounds. Model 2 included age group, and Model 3 included Met-mins/week. Model 4 tested for the interactions of age group × Met*mins/week. GPAQ data was positively skewed and a log transformation was completed to ensure the skewness did not significantly influence the results. The results did not significantly differ between the centered GPAQ data and the log transformed data. For ease of interpretation, the centered GPAQ data was utilized in the final model. The data was analyzed using SPSS (IBM SPSS Statistics Version 25).

Results Study 1

Demographics

The participants (n=54) were normal to overweight, cognitively normal, older (n=26, M=66.2 years, SD=2.59) and younger adults (n=28, M=23.3 years, SD=3.04). The sample was composed of 18.5% African American, 7.5% Hispanic, 74% Caucasian, and consisted of men (31.5%) and women (68.5%). On average participants were highly active (Young M=3661 met-mins/week, Older M=1870 met-mins/week) exceeding weekly physical activity recommendations (500 met-mins/week). Despite the highly active sample, there was a range of activity levels for both age groups (Young range: 760 – 13760 met-mins/week, Older range: 180 – 13200 met-mins/week) with 100% of the young adults meeting the guidelines (500 met-mins/week), and 81% of the older adults meeting the guidelines. All demographics are reported in table 2. For participants physical activity information see Appendix A.

Table 2. Study 1 participants' demographic information

	Young adults (n = 28)	Older adults (n = 26)
Age (years)	23.3 ± 3.04	66.2 ± 2.59^
BMI	26.4 ± 5.21	27.6 ± 5.51
MOCA	28.7 ± 1.09	28.1 ± 1.23*
Education (years)	17.2 ± 2.10	16.3 ± 2.62
Sex	M = 9, F = 19	M = 8, F = 18

Note. Standard deviations are presented with means. Independent sample t-tests were conducted to examine differences between young and older adults. * Indicates p-value <.05, ^ indicates p-value < .01.

Table 3. Study 1 participants' ethnicities

	Young adults (n = 28)	Older adults (n = 26)
White/Caucasian	n = 16	n = 24
African American	n = 8	n = 2
Hispanic	n = 4	n = 0

Table 4. Significance across 4 models for outcomes

	Model 1	Model 2	Model 3	Model 4
RAVLT	df (2,51)	df 1(,50)	df (1,49)	df (1,48)
Trial 1	R^2: 10.9%, n.s.	R^2: 14.3%, n.s.	R^2: 19.8%, n.s.	R^2: 20%, n.s.

Trial 7	R^2: 5.9%, n.s.	R^2: 25.2%, p<.001	R^2: 34.3%, p=.012	R^2: 34.3%, n.s.
Delayed Recall	R^2: 9%, n.s.	R^2: 28.8%, p<.001	R^2: 38.1%, p=.009	R^2: 39%, n.s.
Paired-associates	df (2,51)	df 1(,50)	df (1,49)	df (1,48)
Trial 1	R^2:1.1%, n.s.	R^2: 17.9%, p=.002	R^2: 23.9%, p=.054	R^2: 25.6%, n.s.
Trial 2	R^2: 5.2%, n.s.	R^2: 37.9%, p<.001	R^2: 47.3%, p=.005	R^2: 52.6%, p=.025
Delayed Recall	R^2: 7.6%, n.s.	R^2: 55.5%, p<.001	R^2: 59.9%, p=.024	R^2: 61.8%, n.s.
Stroop task	df (2,51)	df 1(,50)	df (1,49)	df (1,48)
Reaction time	R^2: 2.8%, n.s.	R^2: 22%, p<.001	R^2: 22.2%, n.s.	R^2: 24.6%, n.s.
Accuracy	R^2:12.3%, p=.035	R^2: 24.7%, p=.006	R^2: 25.9%, n.s.	R^2: 27.9%, n.s.
Working memory	df (2,50)	df 1(,49)	df (1,48)	df (1,47)
Reaction time – 2	R^2: 4.9%, n.s.	R^2: 30.2%, p<.001	R^2: 30.5%, n.s.	R^2: 35.4%, n.s.
Reaction time – 3	R^2: 3.1%, n.s.	R^2: 52.3%, p<.001	R^2: 54.4%, n.s.	R^2: 60%, p=.014
Reaction time – 4	R^2: 0.5%, n.s.	R^2: 52.4%, p<.001	R^2: 52.5%, n.s.	R^2: 56.5%, p=.044

Accuracy – 2	R^2: 5.5%, n.s.	R^2: 5.5%, n.s.	R^2: 8.1%, n.s.	R^2: 13.1%, n.s.
Accuracy – 3	R^2: 3.1%, n.s.	R^2: 10.5%, p=.049	R^2: 11.7%, n.s.	R^2: 11.8%, n.s.
Accuracy – 4	R^2: 5.2%, n.s.	R^2: 13.0%, p=.042	R^2: 13.1%, n.s.	R^2: 13.2%, n.s.

Single-item episodic memory

Trial 1. For model 1, 10.9% of the variance was explained for RAVLT trial 1, $F(2, 51) = 3.12$, $p = .053$, but non-significant. After entry of age group, model 2 was non-significant, $F_{change}(1, 50) = 1.98$, $R^2_{change} = 3.4\%$, $p = .166$. For model 3, Met-mins/week was added and found to be non-significant, $F_{change}(1, 49) = 3.38$, $R^2_{change} = 5.5\%$, $p = .072$. Model 4 was non-significant as well.

Trial 7. Model 1 was non-significant $p = .210$. After entry of age group, model 2 was significant, $F_{change}(1, 50) = 12.89$, $R^2_{change} = 19.3\%$, $p = .001$. For model 3, Met-mins/week was added and found to be significant, $F_{change}(1, 49) = 6.75$, $R^2_{change} = 9\%$, $R^2 = 34.3\%$, $p = .012$. Model 4 was non-significant. In the final significant model (model 3), age group ($\beta = -.350$, $p = .007$) and total met-mins/week ($\beta = .325$, $p = .012$) were significant predictors showing that older adults performed 0.350 standard deviations worse than the young adults, and that for every 1 standard deviation increase in total met-mins/week there is a 0.325 standard deviation improvement in trial 7 performance for both age groups.

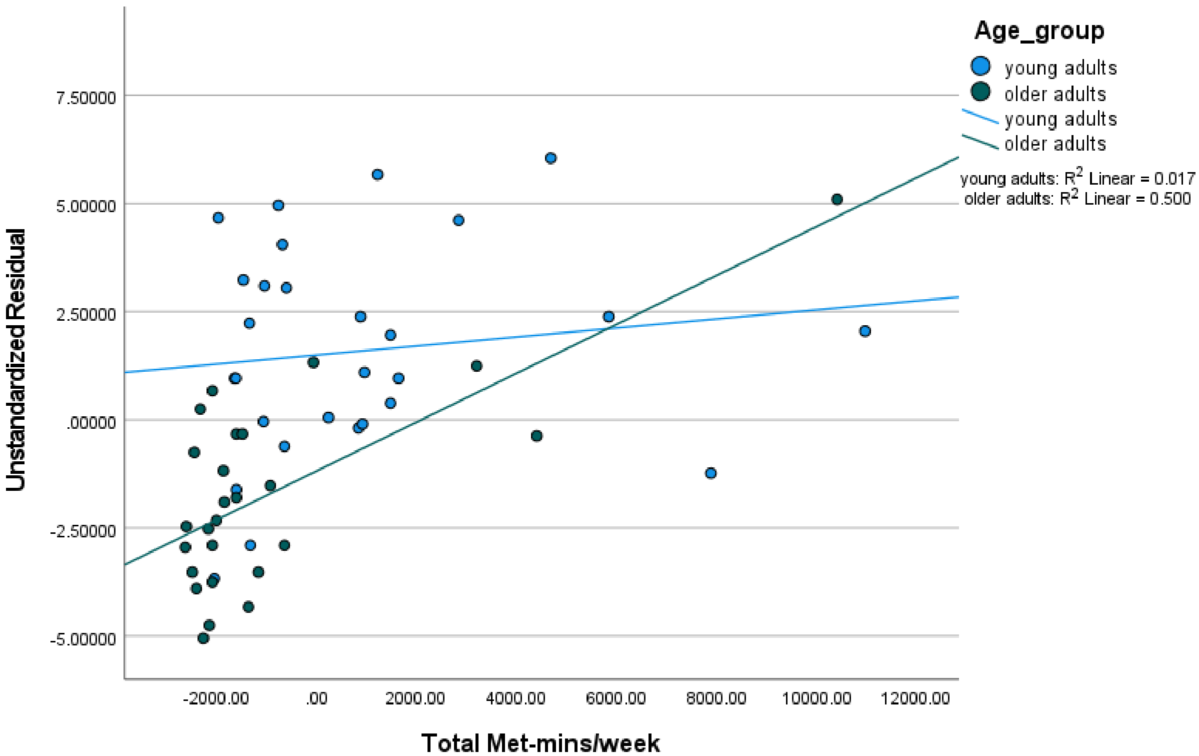
Delayed recall. Model 1 was non-significant. After entry of age group, model 2 was significant, $F_{change}(1,50) = 13.85$, $R^2_{change} = 19.7\%$, $p = .001$. For model 3, Met-mins/week was added and found to be significant, $F_{change}(1,49) = 7.41$, $R^2_{change} = 9.4\%$, $R^2 = 38.1\%$, $p = .009$. Model 4 was non-significant. In the final significant model (model 3), age group (β = -.353, p = .005) and total met-mins/week (β = .330, p = .009) were significant predictors showing that older adults performed 0.353 standard deviations worse than young adults, and for every 1 standard deviation increase in total met-mins/week, there was a 0.330 standard deviation improvement in delayed recall performance for both age groups.

Paired-associates episodic memory

Trial 1. Model 1 was non-significant. After entry of age group, model 2 was significant, $F_{change}(1,50) = 10.22$, $R^2_{change} = 16.8\%$, $p = .002$. For model 3, Met-mins/week was added and found to be marginally significant, $F_{change}(49,1) = 3.91$, $R^2_{change} = 6.1\%$, $R^2 = 23.9\%$, $p = .054$. Model 4 was non-significant. In the final marginally significant model, age group (β = -.337, p = .015) was a significant predictor and total met-mins/week (β = .266, p = .054) was marginally a significant predictor. These predictors were such that performance was better for the young adults by 0.337 standard deviations and for both age groups, a 1 standard deviation increase in total met-mins/week predicted a 0.266 standard deviation improvement in paired-associates short-term memory.

Trial 2. Model 1 was non-significant. After entry of age group, model 2 was significant, $F_{change}(1,50) = 26.37$, $R^2_{change} = 32.7\%$, $p < .001$. For model 3, Met-mins/week was added and found to be significant, $F_{change}(1,49) = 8.76$, $R^2_{change} = 9.4\%$, $p = .005$. With the addition of the age group x total met-mins/week interaction, model 4 was significant, $F_{change}(1,48) = 5.36$, $R^2_{change} = 5.3\%$, $R^2 = 52.6\%$, $p = .025$. In the final significant model (model 4), age group (β = -.481, p < .001) and age group x total met-mins/week interaction (β = .323, p = .025) were significant predictors. See figure 1 for the age group x total met-mins/week interaction which shows that for older adults, a 1 standard deviation increase in total met-mins/week predicted a 0.323 standard deviation improvement in trial 2 performance. Age group was also a negative predictor such that older adults performed 0.481 standard deviations worse than young adults.

Figure 1. Paired associative memory trial 2 performance



Note. The y-axis represents the unstandardized residual for trial 2 performance after controlling for education and sex.

Delayed recall. Model 1 was non-significant. After entry of age group, model 2 was significant, $F_{change}(1, 50) = 53.66$, $R^2_{change} = 47.8\%$, $p < .001$. For model 3, Met-mins/week was added and found to be significant, $F_{change}(1, 49) = 5.44$, $R^2_{change} = 4.5\%$, $R^2 = 59.9\%$, $p = .024$. Model 4 was non-significant. In the final significant model (model 3), age group ($\beta = -.637$, $p < .001$) and total met-mins/week ($\beta = .228$, $p = .024$) were significant predictors showing that older adults performed 0.637 standard deviations worse than young adults, and that for both age groups a 1 standard deviation increase in total met-mins/week predicted a 0.228 standard deviation improvement in delayed recall.

Stroop task

Reaction time. Of the 4 models, only model 2 was significant for Stroop interference reaction time, $F_{change}(1, 50) = 12.34$, $R^2_{change} = 19.2\%$, $R^2 = 22\%$, $p < .001$. In the final significant model, only age group ($\beta = .448$, $p < .001$) was a significant predictor showing that older adults had a 0.448 standard deviations larger Stroop effect on reaction time than the young adults did.

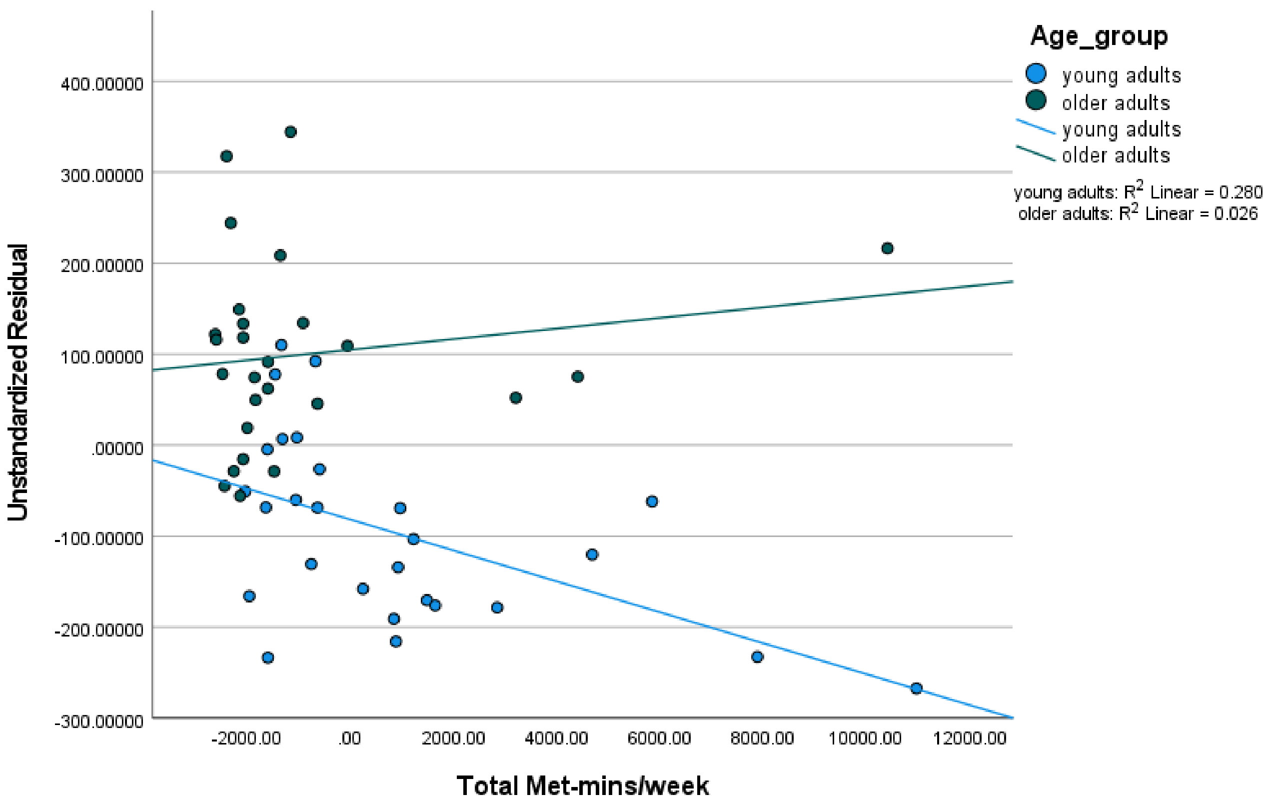
Accuracy. For model 1, 12.3% of the variance was explained for Stroop accuracy interference scores, $F(2, 51) = 3.59$, $p = .035$. After entry of age group, model 2 was significant, $F_{change}(1, 50) = 8.21$, $R^2_{change} = 12.4\%$, $R^2 = 24.7\%$, $p = .006$. Models 3 and 4 were non-significant. In the final significant model (model 2), age group ($\beta = -.359$, $p = .006$) was a significant predictor, and sex was a significant predictor ($\beta = .288$, $p = .025$) showing that performance was better for younger than older adults and for females compared to males.

Spatial working memory

Reaction time – Set size 2. Model 1 was non-significant. After entry of age group, model 2 was significant, $F_{change}(1, 49) = 17.73$, $R^2_{change} = 25.3\%$, $p < .001$. Model 3 was non-significant. With the addition of the age group x total met-mins/week interaction model 4 was non-significant $F_{change}(1, 47) = 3.57$, $R^2_{change} = 4.9\%$, $R^2 = 35.4\%$, $p = .065$. In the final significant model, age group ($\beta = .515$, $p < .001$) was a significant predictor showing that older adults had a 0.515 standard deviations slower reaction time than the young adults on set size 2.

Reaction time – set size 3. Model 1 was non-significant. After entry of age group, model 2 was significant, $F_{change}(1, 49) = 50.66$, $R^2_{change} = 49.3\%$, $p < .001$. For model 3, Met-mins/week was added and found to be non-significant. With the addition of the age group x total met-mins/week interaction, model 4 was significant, $F_{change}(1, 47) = 6.47$, $R^2_{change} = 5.5\%$, , $R^2 = 60\%$, $p = .014$. In the final significant model, age group ($\beta = .677$, $p < .001$), total met-mins/week ($\beta = -.391$, $p = .006$), and age group x total met-mins/week interaction ($\beta = .330$, $p = .014$) were significant predictors. See figure 2 for the age group x total met-mins/week interaction which shows that older adults had a 0.677 standard deviations slower reaction time than young adults, and that for older adults, a 1 standard deviation increase in total met-mins/week predicted a 0.330 standard deviation increase in reaction time.

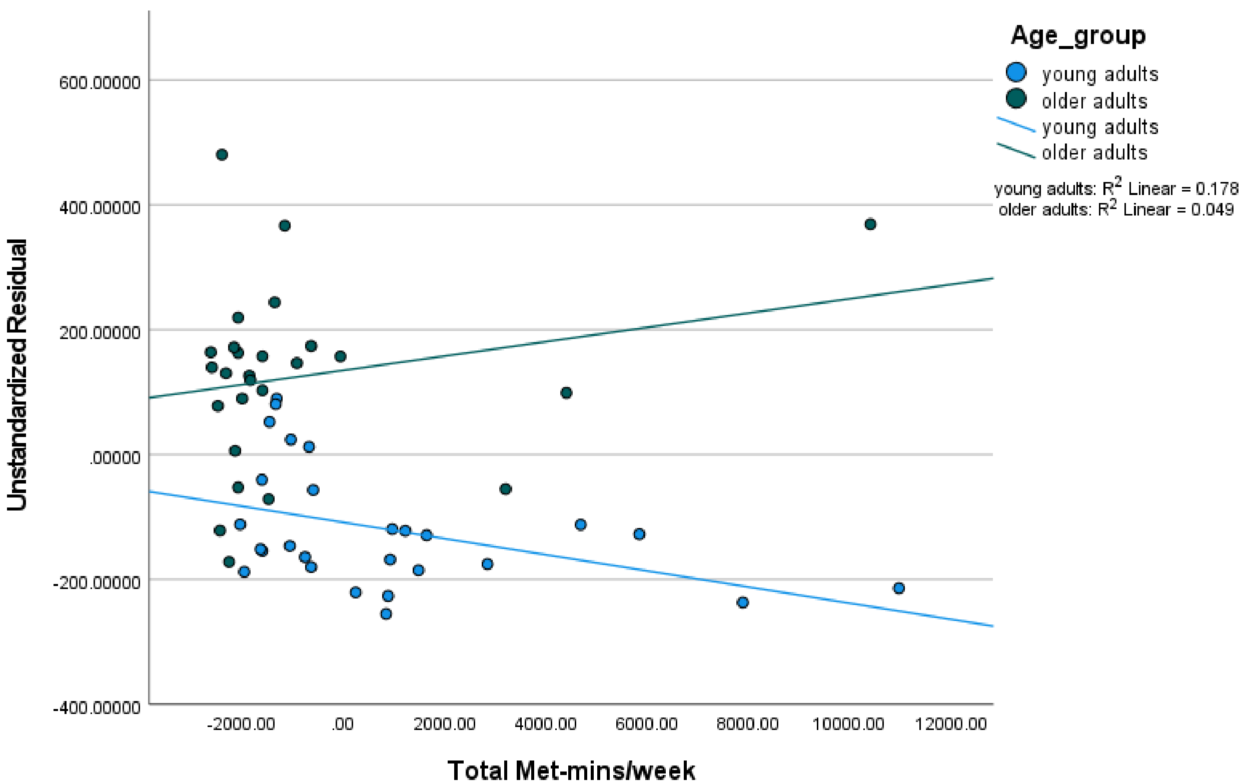
Figure 2. Working memory set size 3 reaction time



Note. The y-axis represents the unstandardized residual for set size 3 reaction time after controlling for education and sex.

Reaction time – Set size 4. Model 1 was non-significant. After entry of age group, model 2 was significant, $F_{change}(1, 49) = 53.47$, $R^2_{change} = 51.9\%$, $p < .001$. For model 3, Met-mins/week was added and found to be non-significant. With the addition of the age group x total met-mins/week interaction, model 4 was significant, $F_{change}(1, 47) = 4.30$, $R^2_{change} = 4\%$, $R^2 = 56.5\%$, $p = .044$. In the final significant model, age group ($\beta = .731$, $p < .001$) was a significant predictor, and the age group x total met-mins/week interaction ($\beta = .280$, $p = .044$) was significant. See figure 3 for the age group x total met-mins interaction which shows that older adults performed significantly slower than young adults, and that for older adults, a 1 standard deviation increase in total met-mins/week predicted a 0.280 standard deviation increase in reaction time.

Figure 3. Working memory set size 4 reaction time



Note. The y-axis represents the unstandardized residual for set size 4 reaction time after controlling for education and sex.

Accuracy – Set size 2. None of the 4 models were significant predictors of accuracy for set size 2.

Accuracy – Set size 3. Of the 4 models, model 2 was a significant predictor of accuracy for set size 3, $F_{change}(1, 49) = 4.08$, $R^2_{change} = 7.4\%$, $R^2 = 10.5\%$, $p = .049$. In the final significant model, age group ($\beta = -.280$, $p = .049$) was a significant predictor and showed that older adults were significantly less accurate than young adults for set size 3.

Accuracy Set size 4. Of the 4 models, model 2 was a significant predictor of accuracy for set size 4, $F_{change}(1, 49) = 4.38$, $R^2_{change} = 7.8\%$, $R^2 = 13\%$, $p = .042$. In the final significant model, age group ($\beta = -.286$, $p = .042$) was a significant predictor showing that older adults were significantly less accurate than young adults for set size 4.

CHAPTER III: STUDY 2

Abstract Study 2

A large body of research has shown that young adults gain cognitive benefits following a single bout of aerobic exercise but not as much research has been completed examining older adults. Despite that, the research to date is promising, showing that older adults appear to gain similar if not greater cognitive benefits following a single bout of aerobic exercise. This study was designed to investigate the effects of a single bout of aerobic exercise on episodic memory, executive functioning, and working memory and how age moderates these effects. This was done by directly comparing a young adult group (20 – 30 years old) to an older adult group (60 – 70 years old). Using a within-subjects design, moderate intensity aerobic exercise (20-min) was either not performed (control condition) or performed (exercise condition) prior to the tasks. Participants completed three visits that included a familiarization visit (see study 1) and two counterbalanced visits where participants completed the two conditions. For study 2, cognitive functioning was assessed via a battery of cognitive tasks assessing episodic, executive functioning, and working memory. On the two counterbalanced visits, participants completed one of the conditions followed by the RAVLT, Stroop task, and the Dot task before completing a delayed (20-min) recall and recognition of the RAVLT. Differences across conditions were assessed using mixed ANOVAs with age group as a between-subject factor. Our results showed that episodic memory was significantly improved following exercise compared to rest for all outcomes. For select aspects of episodic memory (Trials 1 -5, trial 7, delayed recall) our results showed that older adults had significantly larger improvements compared to those of the young adults. The results for executive functioning were more mixed with enhancements following exercise for Stroop accuracy and working memory accuracy at level 2. We also found that for the

hardest portion of the working memory task (level 4), accuracy was significantly improved following the exercise for the older adults but not for the young adults compared to the control visit. It appears that episodic memory is significantly enhanced by an acute bout of aerobic exercise but only select aspects of executive functioning are affected. The implications of these findings are very promising, showing that older adults who have diminished cognitive capabilities (compared to healthy young adults) stand to gain more cognitive benefits from a single bout of aerobic exercise. This could indicate that aerobic exercise as a behavioral treatment could be utilized later in life to potentially counteract some of the ARCD that older adults suffer from.

Introduction Study 2

Numerous studies have shown that an acute bout of aerobic exercise is beneficial on various aspects of cognition with meta-analytic reviews showing a range of effect sizes from small to moderate depending on the cognitive domain being examined (Chang et al., 2012; Etnier et al., 1997; Lambourne & Tomporowski, 2010; Roig et al., 2013). There is also a growing body of literature examining how acute exercise affects memory (Coles, & Tomporowski, 2008; Etnier et al., 2021; Etnier et al., 2016; Hötting et al., 2016; Labban, & Etnier, 2011; Labban, & Etnier, 2018; Netz et al., 2007; Pesce et al., 2009; Segal et al., 2012; Sng et al., 2018; Stones, & Dawe, 1993) and executive functioning (Barella et al., 2010; Byun et al., 2014; Chang et al., 2019; Chang et al., 2011; Peiffer et al., 2015; Slusher et al., 2018; Weng et al., 2015). When reviewed meta-analytically, Roig et al. (2013) concluded that acute exercise has small-to-moderate (SMD = 0.26) effects on short-term memory (STM) and moderate-to-large (SMD = 0.52) effects on long-term memory (LTM). A meta-analysis found that executive functioning was enhanced immediately following (Cohen's d = 0.189) an exercise bout and following a delay (Cohen's d = 0.171) after the exercise bout (Chang et al., 2012).

Only a handful of studies have examined how a single bout of aerobic exercise impacts executive functioning (Alves et al., 2012; Barella et al., Chang et al., 2019; 2010; Peiffer et al., 2015) and episodic memory (Etnier et al., 2021; Netz et al., 2007; Schramke, & Bauer, 1997; Segal et al., 2012) in older adults. In a previous study, Etnier et al. (2021) found that aerobic exercise prior to memory encoding yielded significant STM and LTM improvements for middle age to older adults (50 to 75 years old) compared to a control condition. Segal et al. (2012) found that short-duration vigorous-intensity exercise enhanced visual memory. In contrast to those findings, Schramke and Bauer (1997) found no benefits for walking on STM on a word list paradigm for older adults, and Netz et al. (2007) found no differences between a control group and two exercise groups on Digit Span Forward performance by late middle-aged men and women. Overall, studies testing the potential role of acute exercise in terms of memory enhancement for older adults have yielded mixed findings. To further our understanding of the potential benefits of acute exercise for episodic memory performance, a design was utilized that has previously demonstrated robust findings in both young and older adults (Etnier et al., 2021; Labban & Etnier, 2011; Labban & Etnier, 2018).

In terms of the acute exercise effects on executive functioning in adults, Alves et al. (2012) examined how single bouts of aerobic exercise impacted Stroop and Trail Making task performance in older adults. They found that following a single bout of aerobic exercise, time to complete the Stroop non-color word and color-word portions were significantly reduced compared to the control. Trail Making task performance was not significantly different between the aerobic exercise bout and the control. Barella et al. (2010) found that there were significant improvements in the Stroop task immediately following exercise on the color portion of the task but not on the interference scores. Peiffer et al. (2015) found that flanker reaction time scores and d2 (measure of sustained attention) performance were improved following a 20-min bout of aerobic exercise at 50% and 75% of VO_2 max. Chang et al. (2019) found that their participants had significantly reduced response times for both congruent and neutral conditions on the Stroop task following 20-mins of aerobic exercise. The 20-min bout also resulted in significantly shorter response time on the incongruent trials than all other conditions. Across these studies, the research is promising as each study found that executive functioning was enhanced following a single bout of aerobic exercise in some manner. Despite these promising results, half of the studies discussed above were completed on middle-aged participants.

There is promising research to show that a single bout of aerobic exercise enhances episodic memory and executive functioning in both young and older adults. Despite that, the research to date is mixed in terms of the benefits of acute exercise for older adults in terms of episodic memory and lacking for executive functioning. In addition to these two issues, none of the above-mentioned studies explicitly examined how age group impacts the exercise – cognition relationship since participants were from only one age group. While informative as to how middle-aged and older adults respond cognitively to a single bout of aerobic exercise, these studies do not allow us to make conclusions as to how aging can influence the cognitive changes examined. By comparing groups of young and older adults we can then draw conclusions based off the effect that aging has on the exercise – cognition relationship, not just how older adults respond to a single bout of exercise cognitively.

Therefore, the purposes of study 2 are to 1) examine how a single bout of moderate intensity aerobic exercise impacts episodic memory in both young and older adults and 2) examine how a single bout of moderate intensity aerobic exercise impacts executive functioning in both young and older adults. My hypotheses are 1) that both older and younger adults will have significantly improved episodic memory following a single bout of moderate intensity aerobic exercise, but older adults will have a greater magnitude of improvement. This is based on the cognitive reserve hypothesis indicating that older adults with diminished cognitive reserves have more to gain from activities that improve cognitive functioning (Scarmeas & Stern, 2003; Tan et al., 2017), and previous research conducted in our lab showing that older adults had greater effect sizes (η^2_{partial} for LTM: 0.62 vs. 0.11) following an acute bout of aerobic exercise (Etnier et al., 2021) compared to studies with similar methods on young adults (Etnier et al., 2016; Labban & Etnier, 2011; 2018). I further hypothesize 2) that both older and younger adults will have significantly improved executive functioning following a single bout of aerobic exercise, but older adults will have a greater magnitude of improvement compared to young adults. This is based on the Chang et al. (2012) meta-analysis that found that an acute bout of aerobic exercise has a significant small positive effect on cognitive functioning, and that older adults showed greater effect sizes than young adult samples did (Cohen's d: 0.181 vs. 0.072).

Methods Study 2

Participants

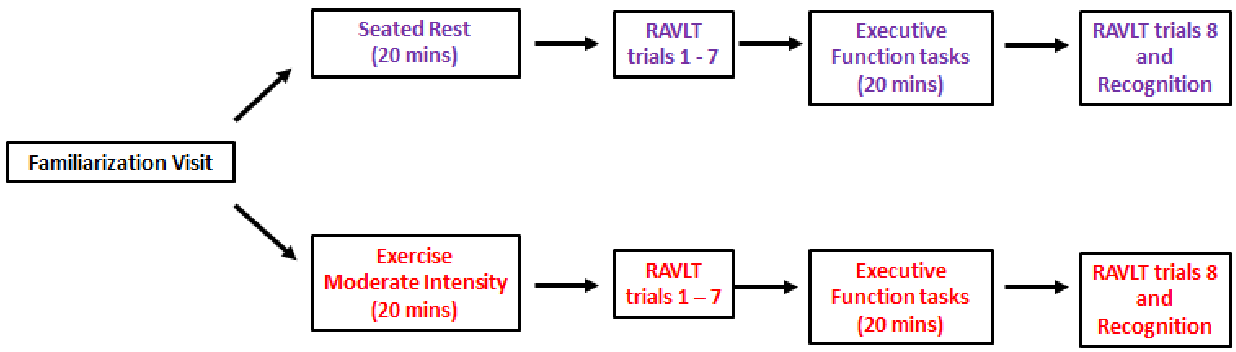
All participants from study 1 who qualified were invited to complete two additional visits to participate in Study 2. The inclusion criteria for participants from study 1 to take part in study 2 were: 20 to 30 (young adult group) and 60 to 70 (older adult group) years old, no presence of cognitive impairment as assessed by the Montreal Cognitive Assessment (MOCA), no clinical conditions that could impact physical activity engagement or cognitive functioning, regularly active (>90 mins per week; GPAQ), and no known disease or injury that restricts exercise. More than 90 minutes per week of physical activity was utilized to ensure that participants were active enough to complete the exercise bout without becoming extraneously fatigued. This threshold has been previously used in our lab to ensure that participants could complete the exercise bout (Etnier et al., 2021). Using the smallest effect size ($\eta^2_{partial}$= 0.16 from delayed recall) from the omnibus tests in Labban and Etnier's studies (Labban & Etnier, 2011; Labban & Etnier, 2018) with α=0.05 and power=0.80, the total sample size required to detect a significant between-groups effect using a mixed ANOVA was estimated to be N = 12 per group (GPower 3.1.9.4). To ensure the study was fully powered at least 15 participants per age group completed the study.

Study design

A mixed design was used with two age groups (young and older adults) and two conditions (exercise and rest; See figure 4 for the study design). The order of conditions and order of the various Rey Auditory Verbal Learning Test (RAVLT) versions were counterbalanced. Participants who met the inclusion criteria had a total of three lab visits. The first visit constituted a familiarization visit where participants were screened for cognitively normality, read, and completed an informed consent, filled out a demographic questionnaire, and then completed a battery of cognitive tasks (data presented in Study 1). During the exercise condition, participants were required to exercise for a total of 25-mins on a stationary recumbent cycle ergometer while watching an educational video with closed captioning. In the control condition, participants sat on the recumbent cycle ergometer watching an educational video with closed captioning. The exercise consisted of a 5-min warm-up and 20-min at moderate intensity (55-65% HRR). This intensity and duration were chosen because of previous research that has shown cognitive enhancements following 20-mins of moderate intensity aerobic exercise (Etnier et al., 2021) and similar studies with roughly the same duration and intensity also showing enhancements in memory (Labban & Etnier, 2011; Labban & Etnier, 2018). Additionally, in a previous meta-analysis, Chang et al. (2012) found that exercise bouts lasting up to 20-mins resulted in significant improvements both immediately following exercise and after a delay. Similar findings were made in terms of intensity of exercise with moderate intensity resulting in significant improvements both immediately and following the bout. The lab visits were scheduled on different days with a minimum of 72 hours between visits. Participants visited the lab at approximately the same time of day for all three visits (within 1-2 hours). Before coming to the lab visits participants were instructed to not engage in any exercise outside of the lab 24-hour prior to coming in and to not eat or use caffeine 2 hours prior to coming in and was confirmed when participants arrived.

While the purpose was not to specifically examine the timing of the exercise bout relative to the memory task exposure, it is important to be aware that the timing of exercise bouts has been found to have an influence on delayed memory performance. These studies suggest that exercise prior to encoding results in better episodic memory performance for STM and LTM (Etnier et al., 2021; Frith et al., 2017; Labban & Etnier, 2011; Labban & Etnier, 2018; Sng et al., 2018). It should be noted though that the temporal proximity of when exercise is completed relative to encoding can influence the strength of this relationship (Roig et al., 2016), and that most of these studies were exclusively focused on effects for young adults except in the case of Etnier et al. (2021). With previous research indicating that exercising prior to encoding of information resulted in the greatest benefit, the current study also utilized that timing for the exercise bout.

Figure 4. Study 2 design



Procedures

Familiarization visit. Participants who met the inclusion criteria were scheduled for their lab visits. During their first visit they were required to read and sign an informed consent form, fill out a demographic questionnaire (age, sex, educational level), fill out the Global Physical Activity Questionnaire (GPAQ), and complete the MOCA. Height and weight were measured using a two-in-one stadiometer and scale with shoes on. Next participants completed a battery of cognitive tasks assessing episodic memory and executive function.

Experimental visits. Before starting the rest or exercise protocol, participants' resting HR was measured for 7-mins. Throughout the lab visits, participants were asked to wear a Polar V800 HR Monitor. Participants were asked to sit quietly, keep their feet flat on floor with legs uncrossed, place their palms facing up on their thighs, and close their eyes. Resting HR was assessed based off an average of the 7-mins, and the participant's heart rate reserve (HRR) was determined using the Karvonen formula (Maximum HR=220-age; Target HR=(MaxHR-RHR) x training % + RHR) (Karvonen et al., 1957). After calculating 55-65% HRR, participants completed the exercise bout (20-mins at 55-65%HRR) during the exercise condition or rested for 20-mins during the control condition. Every 2-min, a researcher recorded the participant's HR, while every 4-min the rating of perceived exertion was obtained using the Borg's 6-20 scale

(Borg, 1982). Participants watched a neutral educational video with closed captioning during all rest and exercise protocols. After the rest or exercise phase, participants were seated at a computer screen. A researcher explained the memory task again and asked if they had any questions. Participants had water available to drink throughout the exercise and the resting protocols at their request. Upon completion of the memory task, the researchers started a 20-min timer for the delayed recall and recognition portion of the memory task. During those 20 minutes participants completed two tasks assessing executive function. Upon completion of those tasks and following the 20-min delay participants completed a free recall-based memory task followed by a recognition memory task.

Measures

Cognitive status. To ensure that participants showed no presence of cognitive impairment, participants were required to complete the MOCA. Scores on the MOCA range from 0 to 30, and individuals who receive a score of 26 or higher were considered to have no cognitive impairment and allowed to participate (Smith et al., 2007). The MOCA has high test-retest reliability (correlation coefficient=0.92, p<.001), internal consistency (Cronbach alpha=0.83), and high validity when compared to the Mini Mental State Exam (r=0.87, p<.001; Nasreddine et al., 2005).

Health status. The ACSM Exercise Pre-participation Health Screening Questionnaire was used to screen participants regarding any cardiorespiratory symptoms, their current activity level, and any known medical conditions (ACSM guidelines for exercise testing and prescription, 2020). Individuals with cardiorespiratory conditions or symptoms that prevent them from engaging in physical activity were excluded from the study. When participants reported previous medical conditions that do not restrict their physical activity participation, they were required to get their physician's permission and signature on a physician release form issued by the Kinesiology department and to submit it to researchers prior to participating in the second lab visit.

Physical activity level. The Global Physical Activity Questionnaire (GPAQ) was used to measure participants' physical activity level. The GPAQ is a self-report measure of physical activity that was selected because it is a valid self-report measure of physical activity for adults ages 18-75 years old. The GPAQ was completed with the participants in a semi-interview style to ensure that participants were not confused as to the different intensities that various types of exercise might fall under and to ensure accurate reporting as to the number of minutes they were engaging in these activities. The GPAQ was created by the World Health Organization and is made up of 19-items that assess time spent performing moderate and vigorous intensity physical activity for three domains; work, travel, and recreational activities (Bull et al., 2009). Physical activity data collected from the GPAQ was used to calculate an individual's metabolic equivalent minutes per week (MET-mins/week). Reliability of the GPAQ is moderate to strong (K = 0.67 to 0.73) across the three domains of physical activity. Concurrent validity assessed by comparing the GPAQ to the International Physical Activity Questionnaire-short form (Lee et al., 2011) is moderate with Spearman's rho coefficients from 0.45 for moderate activity to 0.57 for vigorous activity. In addition, the criterion validity of the GPAQ, which has been assessed by examining the association between GPAQ MET-mins/week and pedometers and accelerometers, is comparable to other self-report measures of physical activity with Spearman's rho coefficients ranging from 0.06 to 0.35 (Bull et al., 2009).

Borg ratings of perceived exertion (RPE). Participants' RPE during the exercise bout was measured using the Borg scale of perceived exertion (Borg, 1982; RPE) which ranges from

6 (No Exertion) to 20 (Maximal Exertion). RPE was measured as a manipulation check in addition to HR to ensure that there were significant differences between conditions in terms of subjective intensity.

Memory task. Verbal single-item learning and memory (Majdan et al., 1996; Schmidt, 1996; Taylor, 1959) were assessed using the RAVLT which is a wordlist memory task consisting of two lists of 15 words. The RAVLT has been validated for various age groups including adults over 50 years of age (de Sousa Magalhães et al., 2012; Rosenberg et al., 1984; Vakil & Blachstein, 1997). Since the creation of the original RAVLT, parallel versions have been created to allow for use in repeated measures designs. RAVLT lists were counterbalanced across participants and conditions. The RAVLT has also been found to have high test-retest reliability using parallel versions of the task. Geffen et al. (1994) found that from 6 to 14 days, the median test-retest correlation was $r = .60$ between parallel versions. Prior to playing the wordlists, the volume was adjusted until the recording could be clearly heard by the participant. Each version of the RAVLT includes two wordlists (List A, List B) that consist of 15 words each which have all been pre-recorded so that all participants will hear the lists of words read in the same fashion. After hearing a wordlist, participants were instructed to repeat as many of the words as they could remember in 30 seconds. It was made clear that the order of their responses does not matter. After the 15 words were read by the recording, the participants were prompted to name as many words as they could remember. This process of list exposure and immediate recall was repeated four additional times for List A (Trials 2 - 5). After the fifth trial, participants were told that they would now hear a different list, called “List B”. After hearing List B, they were asked to repeat as many of the words from List B as possible in 30 seconds (Trial 6). Following Trial 6, and without hearing List A again, participants were asked to repeat as many words from List A as they could remember (Trial 7). Trial 1 was considered a measure of STM. Change in performance across Trials 1-5 was interpreted as an indication of learning. Trial 6 is an interference trial designed to prevent participants from continuing to practice the items from List A. Performance on Trial 7 was considered a measure of long-term memory (LTM - immediate) after a brief delay. Researchers' audio recorded participants' responses during the RAVLT to ensure accurate scoring of responses.

LTM following a longer delay was assessed 20 min later. The primary outcome was a free recall measure. Participants were asked to recall as many words as they could remember from List A (24-hr recall). Following this, participants read a list of words which consist of words from List A, List B, and 20 new words (Majdan et al., 1996). Participants were asked to identify words as being from List A, List B, or a new word from neither list.

Executive function tasks. A computerized version of the classic color-word Stroop task was used to assess executive functioning (Bailey et al., 2012; Stroop, 1935). Previous research has shown high reliability for both latency (as: 0.96 – 0.98) and error rates (as: 0.61 – 0.79) indicating the measures are reliable over time (DiBonaventura et al., 2010). Participants were presented with words printed in an ink color that was either congruent (i.e., the word RED printed in red ink), neutral (i.e., the word CAR printed in red ink), or incongruent (i.e., the word RED printed in blue ink) to the word's meaning. Words were randomly presented for 2.5 seconds, and participants were instructed to respond as quickly as possible to indicate the inked color of the word. Participants respond by pressing a key on a standard keyboard with the index, middle, and ring fingers of their dominant hand. The test included 36 incongruent trials, 36 congruent trials, and 42 neutral trials. A series of 9 practice trials were completed before starting the task to acquaint the participant with the instructions. If the participant did not get at least 5/9 practice trials correct they were instructed to complete the practice again. Stimuli were presented using E-Prime 3.0 software (Psychology Software Tools, Inc., Pittsburgh, PA, USA). Interference scores were created by calculating a difference score between the incongruent and the congruent trials for both accuracy and reaction time. These variables were measures of the interference effect of the Stroop task. Positive scores on Stroop interference reaction time would indicate a larger interference effect and worse performance. Conversely, negative scores on Stroop accuracy interference would indicate worse performance and more of an interference effect.

To assess spatial working memory as a measure of EF, a spatial working memory task was used (Erickson et al., 2011; Erickson et al., 2010; Erickson et al., 2009; Heo et al., 2010). To assess spatial working memory, all participants completed a computerized spatial memory task during familiarization visit and during the 20-min delay following the RAVLT during the two conditions. During the task, a fixation crosshair appeared for 1 second, and participants were instructed to keep their eyes on the crosshair. After the fixation, one, two, or three black dots appeared at random locations on the screen for 500 ms. The dots disappeared from the display for 3-s. During that time, participants were instructed to try and remember the locations of the previously presented black dots. At the end of the 3 second delay, a red dot appeared on the screen in either one of the same locations as the original target black dots (match condition) or at a different location (nonmatch condition). Participants had 2 seconds to respond to the red dot by pressing one of two keys on the keyboard—the “x” key for a nonmatch trial and the “m” key for a match trial. Forty trials were presented for each set size (one, two, or three locations), with 20 trials as match trials and 20 trials as nonmatch trials. Participants were instructed to respond as quickly and accurately as possible. Several practice trials were performed before the task began to reacquaint the participants with the task instructions and responses in addition to being completed during the familiarization visit.

Acute exercise protocol

The exercise was a single bout of moderate to vigorous intensity aerobic exercise performed on a Lode semi-recumbent ergometer exercise bike (Corival Recumbent 929900, Groningen, Netherlands). The exercise began with a 5-min warm-up. Male participants began at 50 watts and female participants started at 40 watts. Watts were increased by 10 every minute until participants reached their target HR zone (55-65%HRR). After the 5-min warm-up, participants were asked to cycle for 20-mins. During cycling, participants were instructed to keep their revolutions per minute (RPM) between 60-80 RPMs. When the participants' HR went beyond their target HR, the watts were decreased by 5-10 watts until their HR returned to the 55-65% HRR range. If their HR did not increase significantly after 2-mins of warm-up, the researcher increased the resistance by 10 watts every 30 seconds until their HR came within 5 beats per minute of the target.

Statistical analyses

Alpha was set at 0.05 for all analyses. Significant interactions were followed up with tests of simple effects. In the case of violations of the assumption of sphericity, a Huynh-Feldt correction was made. In the event of significant findings, partial eta squared ($\eta^2_{partial}$) are presented as a measure of effect sizes, and Bonferroni post-hoc analyses were conducted when appropriate.

Manipulation check

A repeated measures ANOVA was conducted to examine the differences between the two conditions on RPE and HR across both age groups (averaged across measurements taken during exercise) as a manipulation check.

Treatment analyses

To assess differences in STM (Trial 1), learning (trials 1 – 5), LTM (Trial 7), and delayed recall, mixed ANOVAs were conducted to compare performance between conditions (exercise vs. control) and groups (older vs. younger adults). To examine STM differences, a 2 (condition) X 2 (groups) mixed ANOVA was conducted. To examine the learning differences, a 2 (conditions) X 2 (groups) X 5 (trials) mixed ANOVA was conducted. To assess differences on long-term recall (trial 7) and following a delay a 2 (conditions) X 2 (groups) mixed ANOVA was conducted. To assess performance differences on the executive functioning tasks, multiple 2 (conditions) X 2 (groups) mixed ANOVA's were conducted on multiple dependent variables including: Stroop interference scores for both reaction time and accuracy and spatial working memory reaction time and accuracy for each of the three set sizes. A 3 (list) X 2 (groups) mixed ANOVA was conducted on the sum score from trial 1 to delayed recall to examine if there were any differences between the three versions of the RAVLT that were utilized across studies 1 and 2.

Results Study 2

Demographics

The participants (n=33) were normal to overweight, cognitively normal, older (n=16, M=66.6 years, SD=2.0) and younger adults (n=17, M=24.1 years, SD=2.8). On average participants were highly active (Young M=3482 met-mins/week, Older M=2194 met-mins/week) relative to current physical activity guidelines (500 met-mins/week). All demographics are reported in Table 5.

Table 5. Study 2 participants' demographic information

	Young adults (n = 17)	Older adults (n = 16)
Age (years)	24.1 ± 2.8	66.6 ± 2.0^
BMI	25.7 ± 4.3	25.5 ± 3.8
Physical Activity level (Met-mins/week)	3482 ± 2539	2194 ± 3246
MOCA	28.9 ± 1.1	28.4 ± 1.2
Education	17.5 ± 1.8	17.3 ± 2.4
Sex	M = 6, F = 11	M = 4, F = 12

Note. Standard deviations are presented with means. Independent sample t-tests were conducted to examine differences between young and older adults. * Indicates p-value <.05, ^ indicates p-value < .01.

Manipulation check

For RPE, there was a significant main effect for condition, $F(1, 31)=1565.58$, $p<.001$, but not for age group, $F(1,31)=0.053$, p>.05. The age group X condition interaction was non-significant $F(1, 31)=0.053$, p>.05. For HR, there was a significant main effect for condition, $F(1, 31)=2257.40$, $p<.001$, and age group $F(1,31)=23.87$, p<.001 which were superseded by a significant condition X age group interaction, $F(1, 31)=84.61$, $p<.001$. The acute exercise data are reported in Table 6. For total RAVLT score, there was not a significant list effect $F(2, 64)=1.752$, $p>.05$, or a significant list X group interaction F(2, 64)=1.085, $p>.05$ indicating that there were not significant differences across the three versions of the RAVLT used in studies 1 and 2.

Table 6. Study 2 exercise information

	Young adults (n = 17)		Older adults (n = 16)	
	Exercise	Control	Exercise	Control
Average HR	144.1 ± 5.9	73.3 ± 10.1	120.8 ± 4.7	73.0 ± 9.1^
Average RPE	13.9 ± 1.4	6.0 ± 0.0	13.8 ± 0.8	6.0 ± 0.0^
Average HRR %	58.1 ± 2.5	n/a	59.8 ± 1.1^	n/a
Average Watts	101.0 ± 30.4	n/a	61.5 ± 10.5^	n/a

Note. Standard deviations are presented with means. Mixed ANOVA's were conducted to examine differences between young and older adults across conditions for average HR and RPE. * Indicates p-value <.05, ^ indicates p-value < .01.

Table 7. Main and interaction effects for RAVLT

	Age group	Condition	Age group x condition	Trial	Age group x trial	Condition x trial	Age group x condition x trial
Trial 1	n.s.	p<.001	n.s.	n/a			
Trials 1 – 5	n.s.	p<.001	p=.028	p<.001	n.s.	p=.01	n.s.
Trial 7	n.s.	p<.001	p=.048	n/a			
Delayed recall	n.s.	p<.001	p=.021	n/a			

Memory measures

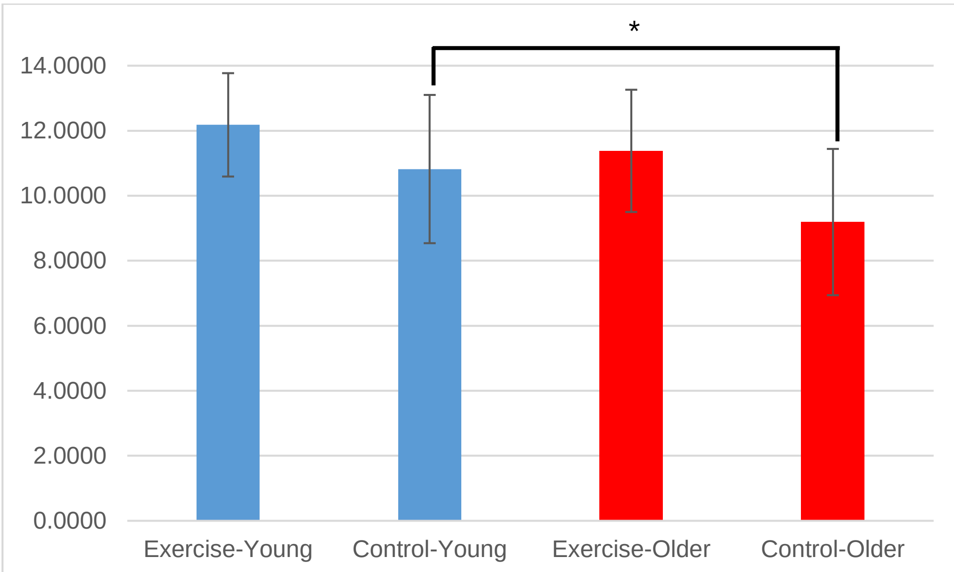
STM. There was a significant main effect for condition, $F(1, 31)=12.47$, $p<.001$, $\eta^2_{partial}=0.287$. The effect of age group, $F(1,31)=2.31$, $p>.05$, and the condition X age group interaction $F(1,31)=0.479$, $p>.05$ were non-significant. Means indicated that both age groups remembered significantly more words following the exercise condition (M=6.76, SD=1.1) compared to the control condition (*M*=6.03, *SD*=1.3). See figure 7 for RAVLT performance across conditions and age groups.

Learning. Results of the 2x2x5 mixed ANOVA comparing performance across trials 1-5 revealed that there were significant main effects for condition, $F(1, 31)=76.20$, $p<.001$, $\eta^2_{partial}=0.711$, and trial, $F(2.75, 85.26)=528.99$, $p<.001$, $\eta^2_{partial}=0.945$, and a non-significant age group effect, $F(1,31)=2.61$, $p>.05$. The interactions of condition x trial, $F(3.58, 110.90)=3.49$, $p=.01$, $\eta^2_{partial}=0.101$, and condition x age group, $F(1, 31)=5.34$, $p=.028$, $\eta^2_{partial}=0.147$, were significant. The interaction of trial x age group $F(3.58, 110.90)=0.11$, $p>.05$ and, condition x trial x age group $F(3.58,110.90)=1.33$, $p>.05$ were non-significant. Examination of the simple effects for the condition x age group interaction indicated that there were significant differences between the young and older adults across trials 1 – 5 during the control condition ($M_{difference}$ = 0.930, *SE* = 0.40, p = .027). These significant differences between the young and older adults were no longer present following the exercise condition ($M_{difference}$ = 0.287, *SE* = 0.40, p = .481). See figure 7 for RAVLT performance across conditions and age groups and table 7 for main and interaction effects across outcomes.

LTM trial 7. Analysis of performance on Trial 7 indicated that there was a significant difference as a function of condition, $F(1, 31)=75.68$, $p=.001$, $\eta^2_{partial}=0.709$ but not for age group $F(1,31)=3.30$, $p>.05$. This was superseded by a significant condition x age group interaction $F(1, 31)=4.21$, $p=.049$, $\eta^2_{partial}=0.119$. Mean differences indicated that both the young adults ($M_{\mathrm{difference}}$ = 1.35, *SE* = 0.28, p <.001), and the older adults ($M_{difference}$ = 2.19, *SE* = 0.29, p <.001), remembered significantly more words following the exercise condition compared to the control condition. Tests of simple effects also indicated that there were significant differences between the young and older adults during the control condition ($M_{difference}$ = 1.64, *SE* = 0.72, p =

.030) but not following the exercise condition ($M_{difference}$ = 0.80, *SE* = 0.68, p = .248). See figure 5 for RAVLT performance on trial 7 by conditions and age groups and table 7 for main and interaction effects across outcomes.

Figure 5. RAVLT performance on trial 7

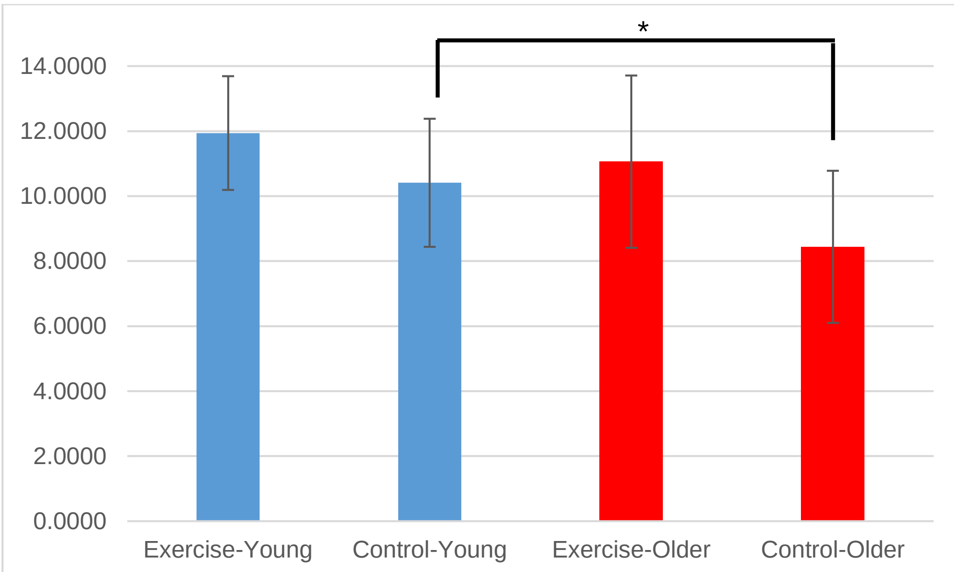


Note. * Indicates p-value <.05, ^ indicates p-value < .01. Standard deviations are presented in error bars.

LTM delayed recall. Analysis of the 20-min recall data revealed a significant condition effect, $F(1, 31)=84.83$, $p<.001$, $\eta^2_{partial}=.732$ but not for age group $F(1,31)=3.82$, $p>.05$. In addition to the main effect of condition, there was a significant interaction of condition x age group $F(1, 31)=5.90$, $p=.021$, $\eta^2_{partial}=.160$. Examination of the means indicated that both the young adults ($M_{difference}$ = 1.53, *SE* = 0.31, p <.001), and the older adults ($M_{difference}$ = 2.63, *SE* = 0.32, p <.001), remembered significantly more words following the exercise condition compared to the control condition. Tests for the simple effects also indicated that there were significant differences between the young and older adults during the control condition ($M_{difference}$ = 1.97, *SE* = 0.75, p = .013) but not following the exercise condition ($M_{difference}$ = 0.88, *SE* = 0.78, p = .266).

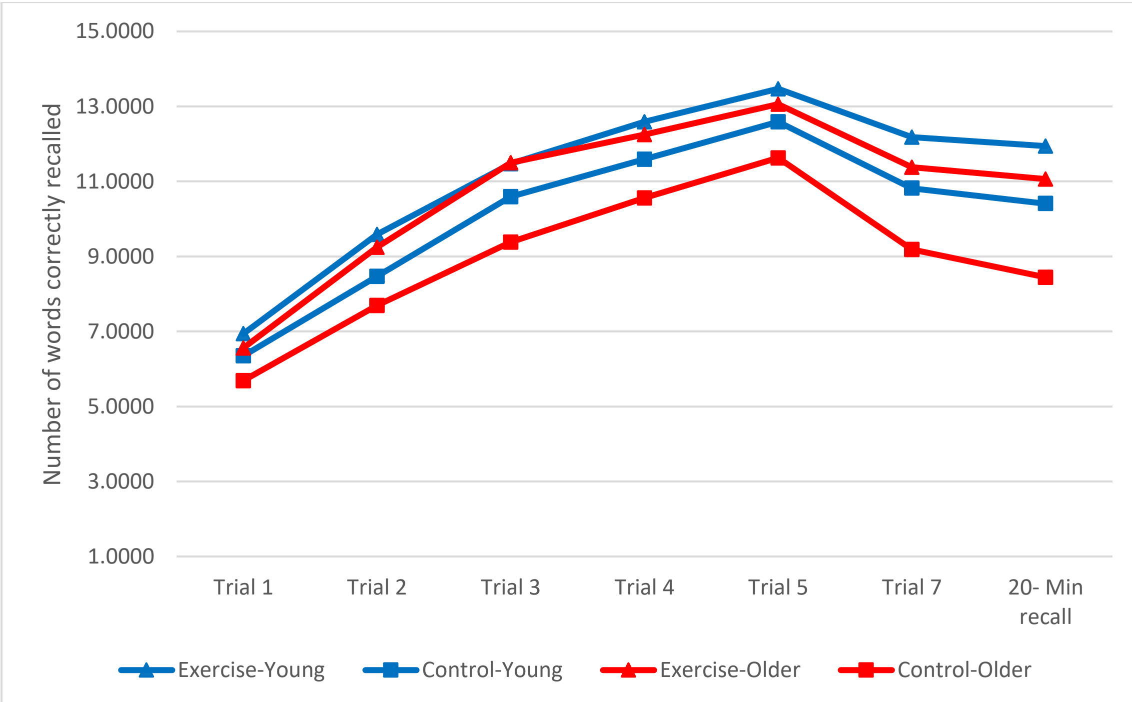
See figure 6 for RAVLT performance on delayed recall across conditions and age groups and table 7 for main and interaction effects across outcomes.

Figure 6. RAVLT performance on delayed recall



Note. * Indicates p-value <.05, ^ indicates p-value < .01. Standard deviations are presented in error bars.

Figure 7. Words recalled across trials and conditions by age group



Executive function measures

Table 8. Main and interaction effects for executive functioning

	Age group	Condition	Age group x condition
Stroop reaction time	p<.001	n.s.	n.s.
Stroop accuracy	n.s.	p = .009	n.s.
WM RT level 2	p<.001	n.s.	n.s.
WM RT level 3	p<.001	n.s.	n.s.
WM RT level 4	p<.001	n.s.	n.s.
WM accuracy level 2	n.s.	p = .018	n.s.
WM accuracy level 3	n.s.	n.s.	n.s.
WM accuracy level 4	n.s.	n.s.	p = .038

Stroop color word task

Reaction time. Analysis of participants reaction time interference scores revealed no significant condition effect $F(1, 31)=0.817$, $p=.373$, but there was a significant age group effect $F(1,31)=35.14$, $p<.001$. Examination of the means indicated that older adults had a significantly larger reaction time interference score than the young adults (M_{diff} = 79.9, SE = 13.48) which indicated that older adults were more severely impacted by the Stroop effect resulting in poorer performance compared to the young adults. There was also not a significant condition x age group interaction $F(1, 31)=1.33$, $p=.258$. See table 8 for main and interaction effects for executive function outcomes.

Accuracy. Analysis of participants accuracy interference scores revealed a significant main effect for condition, $F(1, 31)=7.72$, $p=.009$, $\eta^2_{partial}=.199$. There was not a significant age group effect $F(1,31)=2.95$, $p>.05$ or an interaction of condition x age group $F(1, 31)=0.003$, $p=.955$. Examination of the means indicated that, there was less of the interference effect on accuracy following the exercise condition (M = - 1.18, SE = 0.73), compared to the control condition (M = -3.90, SE = 0.78). See table 8 for main and interaction effects for executive function outcomes.

Spatial working memory task

Reaction time – set size 2. Analysis of participants reaction time for a set size of two revealed no significant main effect for condition, $F(1,30)=0.09$, $p=.756$ but there was a significant main effect for age group $F(1,30)=19.06$, $p<.001$, such that older adults had significantly slower reaction time than the young adults (M_{diff} = 204.6, SE = 46.9). There was not a significant interaction of condition x age group $F(1,30)=0.02$, $p=.885$. See table 8 for main and interaction effects for executive function outcomes.

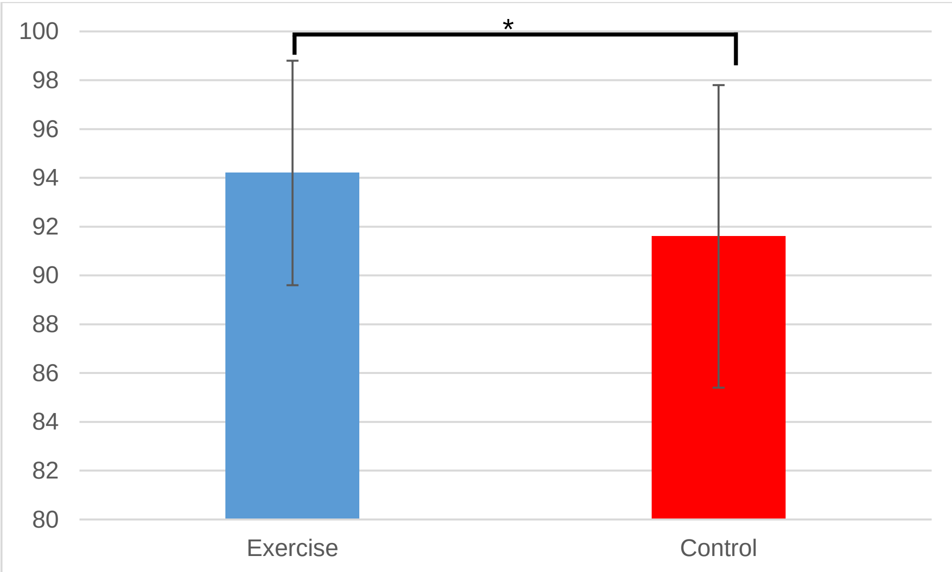
Reaction time – set size 3. Analysis of participants reaction time for a set size of three revealed no significant main effect for condition, $F(1, 30)=0.24$, $p=.626$ but there was a significant main effect for age group $F(1,30)=20.49$, $p<.001$. The means indicated that older adults had significantly slower reaction time compared to the young adults (M_{diff} = 218.5, SE =

48.3). There was not a significant interaction of condition x age group $F(1, 30)=0.36$, $p=.552$. See table 8 for main and interaction effects for executive function outcomes.

Reaction time – set size 4. Analysis of participants reaction time for a set size of four revealed no significant main effect for condition, $F(1, 30)=0.42$, $p=.523$ but there was a significant effect of age group $F(1,30)=26.66$, $p<.001$. Again, the older adults had significantly slower reaction time than the young adults ($M_{diff} = 240.6$, SE = 47.5). There was not a significant interaction of condition x age group $F(1, 30)=0.08$, $p=.786$. See table 8 for main and interaction effects for executive function outcomes.

Accuracy – set size 2. Analysis of participants accuracy for a set size of two revealed a significant main effect for condition, $F(1, 30)=6.27$, $p=.018$, $\eta^2_{partial}=.173$ but not for age group $F(1,30)=0.825$, $p>.05$. There was not a significant interaction of condition x age group F(1, 30)=0.95, $p=.339$. Examination of the means showed that accuracy during the exercise condition was significantly greater than during the control condition (See figure 8). See table 8 for main and interaction effects for executive function outcomes.

Figure 8. Working memory set size 2 accuracy

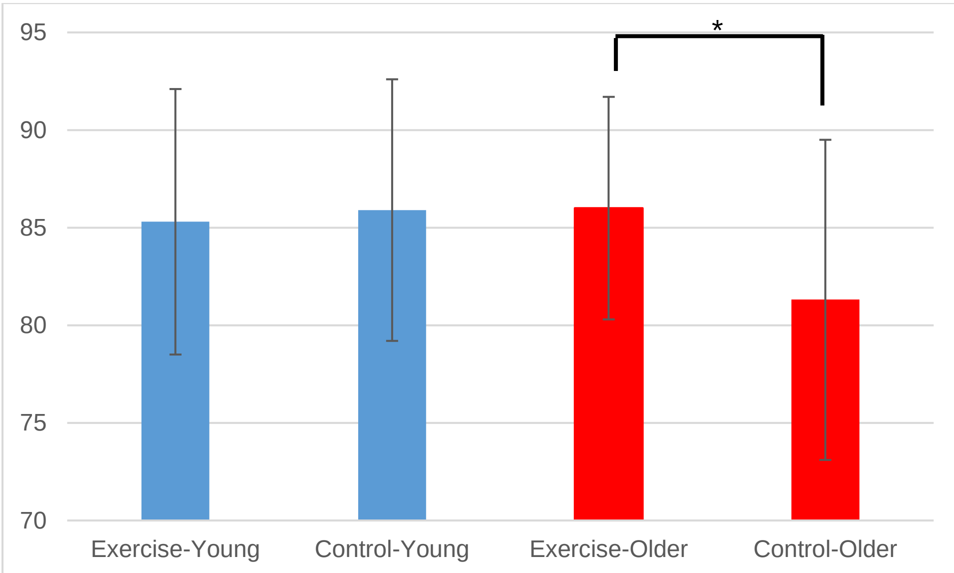


Note. * Indicates p-value <.05, ^ indicates p-value < .01. Standard deviations are presented in error bars.

Accuracy – set size 3. Analysis of accuracy for a set size of three revealed no significant main effects for condition $F(1, 30)=0.04$, $p=.842$ or age group $F(1,30)=0.174$, p>.05. There was also not a significant interaction of condition x age group $F(1, 30)=0.003$, $p=.956$.

Accuracy – set size 4. Analysis of accuracy for a set size of three revealed no significant main effects for condition, $F(1, 30)=2.84$, $p=.102$ or age group $F(1,30)=0.827$, $p>.05$. There was a significant interaction of condition x age group $F(1, 30)=4.71$, $p=.038$, $\eta^2_{partial}=.136$. Examination of the means indicated that older adults had significantly higher accuracy following the exercise condition (M=86.0%, SE=1.6) compared to the control condition (M=81.3%, SE=1.9; p = .013). Young adults showed no significant differences between the exercise condition (M=85.3%, SE=1.5) and the control condition (M=85.9%, SE=1.8, p = .725; See figure 9). See table 8 for main and interaction effects for executive function outcomes.

Figure 9. Working memory set size 4 accuracy performance



Note. * Indicates p-value <.05, ^ indicates p-value < .01. Standard deviations are presented in error bars.

CHAPTER IV: DISCUSSION

Study 1

The aim of this study was to examine how aging might moderate the relationship between subjectively measured physical activity level and cognitive functioning. Using a cross-sectional design, young and older adults completed questionnaires assessing demographics, health history, physical activity level, and social engagement. Following these participants completed a battery of cognitive tasks measuring single-item episodic memory, paired associative episodic memory, and executive function.

Single-item episodic memory outcomes

None of the four models used were significant predictors of RAVLT trial 1 performance. For trial 7 and delayed recall, it was found that age group and total met-mins/week were significant predictors. Older adults remembered significantly fewer words compared to the young adults, and for both age groups total met-mins/week was a positive predictor such that increased levels of physical activity predicted better performance on long-term memory outcomes for both age groups. There was no evidence that age group moderated the effects of physical activity on trial 7 or delayed recall performance.

These findings were surprising given the number of studies that have shown that physical activity is related to memory performance (Etnier et al., 2021; Hayes et al., 2015; Roig et al., 2013). Previous research in cognitive psychology has shown that associative memory is more severely impacted by aging than episodic memory (Buchler & Reder, 2007; Craik, 1983, 1986; Healy et al., 2005; Old & Naveh-Benjamin, 2008). This might indicate that for single-item episodic memory, the age-related deficits are not severe enough for engagement in physical activity to have a greater beneficial effect that it would for young adults. It is also possible that the subjectively used measure of physical activity engagement was not sensitive enough compared to objective measures such as accelerometers. Participants could have a bias for reporting greater physical activity levels than they are engaging in which could skew the data such that the individuals who are truly engaging in more activity cannot be discerned from those who are overreporting. Despite that, if all participants are overreporting their physical activity engagement we would not expect this to have a significant effect on the results as all physical activity levels would be overinflated.

Paired-associates episodic memory outcomes

For trial 1, trial 2, and delayed recall, it was found that both age group and physical activity level were significant predictors. Results showed that older adults performed significantly worse than young adults and that greater levels of physical activity engagement were positively related to performance with more words remembered for each trial. For trial 1 and delayed recall, there was no evidence that age group moderated the effects of physical activity level. For trial 2, there was a significant interaction in model 4 such that older adults benefited more from physical activity engagement in terms of their paired associative trial 2 performance compared to the young adults.

These findings were partially in alignment with the hypotheses. As discussed above, a large body of work in cognitive psychology has shown that associative memory is severely impacted by aging (Craik, 1983, 1986; Old & Naveh-Benjamin, 2008). This in combination with similar work that has been done before (Hayes et al., 2015), although they used objectively measured physical activity, led to the hypothesis that the older adults would show a stronger relationship between total met-mins/week and performance across the three trials assessing associative memory. The lack of consistent findings across the three trials could be due to a few factors. One is the use of a subjective measure of physical activity engagement. It is possible that the measure of physical activity engagement was not sensitive enough compared to objective measures such as accelerometers (Prince et al., 2008; Steene-Johannessen et al., 2016). Participants could have a bias for reporting greater physical activity levels than they are engaging due to societal acceptance of being fit and exercising, which in could have skewed the data making it difficult to truly examine how physical activity engagement has a protective effect on cognitive functioning as we age.

One possibility for the current findings is that for select aspects of cognitive functioning, older and younger adults both stand to gain similar benefits for being more physically active. While the cognitive reserve hypothesis would lead us to believe that older adults with their diminished cognitive reserves/functioning would stand to gain more from exercise engagement (Tan et al., 2017), the benefits might be more related to duration of engagement. Beginning to exercise later in life could begin to slow down an individuals' rate of cognitive decline, but it would not necessarily put them at the same functioning level of an individual the same age who has been exercising for decades. The above results can partially show that older adults' physical activity engagement is more strongly related to associative memory performance, but the strength of this relationship compared to young adults might not be strong enough to have noticeable/detectable differences. These results could indicate that later in life, older adults tend to gain the same magnitude of benefits for physical activity engagement that young adults do. If this is the case, behavioral interventions targeting middle-aged adults could be highly important as engaging in these behaviors earlier in an individuals' life could slow down the rate of cognitive decline they experience with aging over a longer time period.

Stroop color word outcomes

For accuracy and reaction time interference, it was found that age group was a significant negative predictor of performance on the Stroop task. Physical activity level and the interaction of physical activity level by age group were not significant predictors of performance. These findings were not completely surprising given the meta-analytical evidence that has shown that exercise has a small effect on executive functioning across multiple populations (Chang et al., 2012) compared to the effects exercise has on memory (Roig et al., 2013). These findings fall in line with the previous work in cognitive psychology showing that aging has a significant negative impact on executive functioning (Brennan et al., 1997; Crawford et al., 2000; Fjell et al., 2017; Grieve et al., 2007; Mejia et al., 1998). Despite that, the results were surprised that even the main effect of total met-mins/week was not significant for either Stroop accuracy or reaction time interference. The lack of significant findings for physical activity level could be due to the current study being underpowered to examine how physical activity level is related to executive functioning.

The power-analysis for the current study was conducted using medium effect sizes from studies examining how exercise engagement is related to memory performance specifically (Hayes et al., 2015; Roig et al., 2013). When examining episodic memory, a delay is used from completion of initial exposure to stimuli (encoding) to when participants will be tested on their retention of the content (retrieval). This inherent design allowed for 20 minutes of time from the completion of RAVLT trials 1 – 7, to when they will complete a free recall and recognition task. While it was ambitious to examine multiple aspects of cognitive functioning, the current study appears to be underpowered to detect the smaller magnitude effects that physical activity engagement has been shown to have on executive functioning.

Spatial working memory outcomes

None of the four models were significant predictors of spatial working memory accuracy for level 2. For accuracy at levels 3 and 4, age group was a significant negative predictor of performance but total met-mins/week and the interaction between the two were non-significant. There are a few explanations as to the lack of significant findings related to the executive functioning outcomes. As discussed above, the power-analysis for the current study was conducted using effect sizes from studies examining how physical activity level are related to memory performance specifically (Hayes et al., 2015; Roig et al., 2013). This in combination with the small effects that exercise has on executive functioning (Chang et al., 2012) could have resulted in our lack of findings. Even though physical activity level was not a significant predictor of working memory accuracy across the three levels, all the beta coefficients were in the correct direction indicating that greater levels of physical activity would have a positive impact on accuracy performance. This should be read with caution as none of these models or coefficients were significant. This just gives additional evidence that for the current study we were underpowered to examine this relationship due to the nature of the design being focused on memory performance.

For working memory reaction time, age group was a negative predictor for levels 2, 3, and 4. For level 3, total met-mins/week was also a significant predictor. In addition, for levels 2, 3, and 4, the interaction of age group x total met-mins/week was a significant predictor. The interaction showed that young adults had a stronger positive relationship with total met-mins/week compared to the older adults where increases in total met-mins/week predicted faster reaction times for young adults but not for older adults.

These findings were surprising as they opposed majority of the previous work discussed. Numerous studies have found that across multiple age groups physical activity is related to cognitive functioning (Boucard et al., 2012; Chang et al., 2012; Etnier et al., 1997; Falck et al., 2017; Hayes et al., 2015; Roig et al., 2013). When examined meta-analytically, these studies find that older adults tend to gain more benefits from physical activity engagement than other age groups do (Chang et al., 2012; Lambourne & Tomporowski, 2010; Ludyga et al., 2016). Despite that, the current findings here show that the older adults had little to no relationship between their physical activity engagement and spatial working memory reaction time while the young adults had a stronger significant relationship between the two.

One potential interpretation of these findings is that physical activity engagement could have select beneficial effects on various aspects of cognitive functioning with aging. By this we mean that the atrophy in regions of the brain associated with spatial working memory could potentially be severe enough as we age, that physical activity engagement later in life might be too late for older adults to experience the benefits we traditionally see. Research has shown that the hippocampus, medial temporal lobes, and the prefrontal cortex are related to spatial working memory (Courtney et al., 1998; Ren et al., 2019; van Asselen et al., 2006). These areas of the brain are required for the formation of spatial representations of an environment and are also known to play a key role in episodic memory. The fact that these areas of the brain are related to episodic memory, make these findings even harder to interpret as similar findings for our the tasks examining single-item and associative episodic memory were expected. It is possible that the regions of the brain involved in various cognitive tasks could have a moderating effect on the relationship between total met-mins/week and cognitive functioning. Greater atrophy in one region of the brain or white matter tracts connecting regions might limit the beneficial effects exercise can have. If an older adult has significant deficits in their cognitive abilities as a result of severe atrophy or deterioration in the brain, physical activity engagement might not be capable of reversing severe ARCD due to the severity of those changes.

It is also possible that using subjective measures of physical activity level could have skewed our results. Participants self-report data on their physical activity engagement was positively skewed which is a common problem with assessments such as these. Alternative options were explored such as log transforming the data, but these changes did not have a significant impact on the results so the original total met-mins/week was used. The positively skewed data could have an impact on the effects we are examining though this type of distribution is common with self-report physical activity data. Despite our inconsistent findings for spatial working memory reaction time as it relates to the research that has been previously completed, our results did show, that for young adults' engagement in more physical activity was related to enhanced reaction time on a task assessing spatial working memory.

Strengths and limitations

There are several limitations in Study 1. The primary limitation of this study is the use of a cross-sectional design which precludes conclusions regarding cause-and-effect. However, there is substantial research evidence supporting a positive causal link between physical activity engagement and cognitive functioning (Boucard et al., 2012; Chang et al., 2012; Etnier et al., 1997; Falck et al., 2017; Hayes et al., 2015; Quan et al., 2018; Roig et al., 2013; Ruiz et al., 2010; Sibley & Etnier, 2003). A second limitation of this study is that the physical activity measure is a self-reported questionnaire that asked participants to recall the amount of activity they engaged in under various settings. Using a device-based measures of physical activity engagement such as an accelerometer would have yielded more objective information than subjective questionnaires. Despite that, using an objective measure of physical activity engagement would have had its own issues. Devices such as accelerometers are both expensive and require more participant burden because they need to be worn for multiple days. These were two of the main reasons that self-report questionnaires of physical activity engagement were used as they are free and easily accessible by other researchers for replication in the future. A third limitation of the current study is that 100% of the young adults and 81% of the older adults met physical activity guidelines (>500 met-mins/week). While the goal of this study was to recruit a full range of physical activity levels, it appears that young adults who were physically active self-selected to volunteer over individuals who were not engaging in physical activity already. A similar conclusion could be made regarding the older adults with only 19% of participants not meeting physical activity guidelines. This could be due to the possibility that individuals who volunteer for studies on exercise tend to already be exercising in their own free time. Not having a full range of physical activity levels could have impacted the results such that with so few individuals below the guidelines, we did not have a true representation as to the impact exercise has on cognitive functioning when comparing individuals who are sedentary, to those who are exercising regularly.

Conclusion

These findings present evidence that age group indeed had a negative relationship with cognition, and that physical activity engagement is positively related to select aspects of cognitive functioning. Physical activity level was significantly related to select aspects of episodic memory and executive function in both age groups, and for certain outcome variables, older adults benefited greater compared to the young adults and vice versa. For single-item episodic memory, we found no evidence that our models were significant predictors of RAVLT trial 1 performance. For trial 7 and delayed recall, we found that age group was a significant negative predictor and total met-mins/week was a significant positive predictor. There was no evidence that age group moderated the effects of physical activity level on trial 7 and delayed recall performance.

These findings may have important public health implications. It has been reported that nearly 40% of people older than 65 years (16 million people) have age-related memory impairments in the United States alone. Currently, more than 16 million Americans live with MCI, resulting in an estimated additional $56 billion yearly for healthcare costs (Centers for Disease Control [CDC], 2011). In addition, research has shown that there are ARCD's in healthy, normally functioning middle-aged adults as early as 40 – 50 years old (Park, 2009; Jones & Conrad, 1933; Hedden & Gabrieli, 2004). ARCD is a serious problem that should be addressed throughout the lifespan, not only later in life. With the older adult population continually growing, developing cost-effective interventions to minimize healthcare costs associated with cognitive impairment are critical. More research needs to be conducted on the exercise – cognition relationship across the lifespan so we can fully understand the cognitive benefits related to exercising and how practitioners can best prescribe exercise to help individuals.

Study 2

The aim of this study was to investigate the effects an acute bout of aerobic exercise has on cognitive functioning and how aging might moderate that relationship. Using a mixed design, we asked young and older adults to complete 20 minutes of moderate-to-vigorous intensity aerobic exercise and 20 minutes of rest on separate days. We assessed the differences in responses to exercise versus rest on measures of single-item episodic memory and executive function.

Single-item episodic memory outcomes

There were significant differences in single-item episodic memory performance following exercise compared to following rest. There were significant condition effects for trial 1 (STM), trials 1 – 5 (learning), trial 7, and delayed recall. This indicated that for both age groups, completing a 20-min bout of aerobic exercise resulted in participants recalling significantly more words compared to the control condition. In addition, there was also a significant age group x condition interaction for trials 1 – 5, trial 7, and delayed recall. Across these interactions it was consistently found that during the control condition, older adults performed significantly worse than young adults which is not surprising given the number of studies showing ARCD in episodic memory. Interestingly, following the exercise condition, these differences in RAVLT performance were no longer significant due to the larger improvement that then older adults had compared to the improvements in the young adults. These results provide evidence that the older adults did indeed benefit more from a single bout of aerobic exercise than the young adults did. These findings are in alignment with some of the previous work completed on this topic showing that older adults should have greater effect sizes compared to studies on young adults with similar methods (η^2_{partial} for LTM: 0.62 vs. 0.11, Etnier et al., 2021; Etnier et al., 2016)

In a recent meta-analysis, it was reported that acute exercise benefits memory performance (Roig et al., 2013). This meta-analysis indicated that young adults had greater effect sizes compared to older adults following a single bout of aerobic exercise (Roig et al., 2013). Though the authors do caution readers that the number of studies used to calculate these effect sizes were small. One recent study examining this topic found that older adults did have significant improvement in memory performance following a single bout of aerobic exercise compared to a control condition (Etnier et al., 2021). Using a similar design as previous work completed on young adults (Labban & Etnier, 2018), the work from Etnier et al. (2021) had greater effect sizes compared to the studies with young adult participants. The current results corroborate the findings of multiple studies that a single bout of aerobic exercise is beneficial for episodic memory performance (Etnier et al., 2021; Labban & Etnier, 2011, 2018; Roig et al., 2013). The additional findings that age moderates this relationship is not corroborated by previous research but the lack of studies examining the effects of a single bout of aerobic exercise on episodic memory performance in older adults make this unsurprising.

Stroop color word outcomes

There were select significant differences in Stroop Color Word performance following exercise compared to following rest. There was a significant condition effect for accuracy interference but no condition effect for reaction time interference. The results indicated that for both age groups, completing a 20-min bout of aerobic exercise resulted in participants having less of an interference effect on their accuracy at performing the Stroop task compared to the control condition. There was also no evidence that the older adults benefited more from a single bout of aerobic exercise than the young adults did. These findings are partially in alignment with some of the previous work completed examining how a single bout of exercise impacts executive functioning.

In recent meta-analyses, it has been consistently found that an acute bout of exercise benefits executive function (Chang et al., 2012; Lambourne & Tomporowski, 2010; Ludyga et al., 2016; McMorris & Hale, 2012). In addition to that, when age of participants was considered as a moderator, it has been shown that there are larger benefits for older adults (Chang et al., 2012; Ludyga et al., 2016). The findings here were unexpected, as they do not corroborate the findings of multiple meta-analyses showing that older adults should have greater effect sizes compared to other age groups. A potential explanation for the lack of a significant age group-based interaction effect could be due to the delay between exercise and completing of the Stroop task and the duration of the exercise bout.

The average time delay from the completion of exercise to when participants completed the Stroop task was approximately 10 minutes. This was the amount of time it took participants to complete the exercise and indicate to the researcher they were ready to start cognitive testing (2 minutes on average), and complete trials 1 – 7 of the RAVLT (8 minutes). The benefits of exercise on cognition may be affected by the time-delay from exercise to start of testing. A post-exercise cut off for the positive effects of acute exercise on cognition has been suggested by meta-analytic findings at 15 minutes (Chang et al., 2012; Lambourne & Tomporowski, 2010). While the current study did adhere to the suggested time-delay from previous meta-analyses, this in combination with other unaccounted for factors could have resulted in the lack of the significant condition effect for reaction time interference, and the lack of any age group by condition interactions for both outcome variables.

In addition, the duration of exercise may have affected the results. Chang et al. (2012) found that 11-20 minutes of exercise is the ideal duration of exercise to benefit cognitive performance with smaller magnitude positive effect with greater than 20 minutes. The current study utilized 20 minutes of exercise as suggested by Chang et al. (2012), but the current study also utilized a 5-minute warmup which could be considered part of the overall exercise bout making it 25 minutes. This design was utilized because one of the main outcomes from this study was episodic memory measures and previous studies have used similar designs that resulted in significantly improved episodic memory performance (Etnier et al., 2021; Labban & Etnier, 2011; Labban & Etnier 2018) This decision may have influenced the effects on executive function.

The duration of the exercise could have resulted in the lack of a significant condition effect for reaction time, and the lack of age group by condition effects. Previous work has shown that the benefits of an acute bout of exercise on cognition have been small in magnitude, with other factors influencing the magnitude of the relationship. Despite the lack of a significant condition effect on reaction time, and no significant interactions for either accuracy of reaction time, we did find that following an acute bout of aerobic exercise, there were significant beneficial effects on accuracy interference for both age groups compared to the control condition.

Spatial working memory outcomes

For the condition by age group interaction on accuracy level 4, the simple effects showed that during the control condition, there were significant differences between young and older adults in terms of their accuracy. Interestingly, during the exercise condition there were no longer significant differences between the young and older adults on their accuracy during level 4. This could indicate that the older adults did indeed benefit more than the young adults because the significant differences found during the control condition were no longer present between the two age groups following the exercise condition. The current findings are partially in alignment with some of the previous work examining how a single bout of exercise impacts executive functioning.

As discussed above, previous meta-analyses, have consistently found that an acute bout of exercise benefits executive function (Chang et al., 2012; Lambourne & Tomporowski, 2010;

Ludyga et al., 2016; McMorris & Hale, 2012) and that there should be larger benefits for older adults (Chang et al., 2012; Ludyga et al., 2016). The findings from study 2 are inconsistent with previous research as there was only a significant condition effect on accuracy level 2, a significant condition by age group interaction for accuracy level 4, but no other significant main effects or interactions for reaction time levels 2, 3, and 4, or for accuracy level 3. Some of the findings here were unexpected, as they do not corroborate the findings of multiple meta-analyses showing that a single bout of exercise should result in enhanced executive functioning, and that older adults should have greater effect sizes compared to young adults.

The average time delay from the completion of exercise to when participants completed the spatial working memory task was approximately 15 minutes. This was the amount of time it took participants to indicate to the researcher they were ready to start cognitive testing (2 minutes on average), complete trials 1 – 7 of the RAVLT (8 minutes) and complete the Stroop task (5 minutes). As discussed, previous meta-analyses have found that for an acute bout of exercise to have its greatest effects on executive functioning, the task must be completed within 15 minutes (Chang et al., 2012; Lambourne & Tomporowski, 2010). While the current study did adhere to the suggested time-delay from previous meta-analyses, this was just met as the participants began the spatial working memory task at approximately 15 minutes following exercise. Despite that, this task takes participants approximately 12 minutes to complete meaning that upon completion of the task nearly 27 minutes had elapsed since the cessation of exercise.

The power-analysis for the current study was conducted using effect sizes from studies examining how an acute bout of aerobic exercise impacts episodic memory. When examining episodic memory, a delay is used from completion of initial exposure to stimuli (encoding) to when participants will be tested on their retention of the content (retrieval). This inherent design in this case allowed for 20 minutes of time from the completion of RAVLT trials 1 – 7, to when they completed a free recall and recognition task. This design allowed the researchers to examine other cognitive domains within the 15-minute window that was suggested by previous meta-analyses (Chang et al., 2012; Lambourne & Tomporowski, 2010). While it was ambitious to examine multiple aspects of cognitive functioning, the current study appears to be underpowered to detect the smaller magnitude effects that exercise has been shown to have on executive functioning. In reconducting a power analysis (η^2_{partial}= 0.06 from spatial working memory task) using an effect size that represented the median of the observed range of findings, with α=0.05 and power=0.80, the total sample size required to detect a significant between-groups effect using a mixed ANOVA was estimated to be N = 64. The current study while powered to examine the effects that acute exercise had on memory performance, appears to have been underpowered to detect the smaller magnitude effects on executive functioning.

The delay from the completion of the exercise bout to beginning the spatial working memory task could have resulted in the lack of a significant condition effects for reaction time levels 2, 3, and 4, or for accuracy level 3. It is also possible that the current study is underpowered to detect the effects that an acute bout of exercise has on executive functioning. With the sample size of this study being based on episodic memory outcomes, the smaller effects usually found with regards to executive functioning might just not be detectable or robust enough without a larger sample of young and older adults. Examination of the effect sizes and observed power for reaction time level 2 ($\eta^2_{partial}$ = .003, power = .061), 3($\eta^2_{partial}$ =.008, power =.076), 4($\eta^2_{partial}$ = .014, power = .096), and for accuracy level 3 ($\eta^2_{partial}$ = .001, power = .054) showed that the effects were extremely small with very low power indicating the even with a larger sample size than the current study, a condition effect would be unlikely. Despite that, there were significant beneficial effects on accuracy at level 2 and a significant age group by condition interaction for accuracy at level 4. This interaction indicated that the significant difference in performance on the most difficult aspect of the spatial working memory task during the control condition, were no longer present following the exercise condition and young and older adults had similar performances.

Strengths and limitations

This study has multiple strengths. This is one of the first studies to investigate how age group moderates the effects of acute aerobic exercise on cognitive functioning. The evidence provides a meaningful contribution to the literature by showing that exercise can affect episodic memory and executive functioning in both young and older adults and that older adults do indeed gain more cognitive benefits from this single bout on select aspects of cognitive functioning. To investigate these relationships, we utilized a within-subjects, counterbalanced design.

Despite these strengths, this study has its limitations. While the goal of the current study was to examine how aging impacts the exercise – cognition relationship, the current study utilized a cross-sectional design and so ultimately examined how age group moderated the exercise – cognition relationship. Readers should interpret the results with caution as the study design does not allow for an examination of "aging" per se. The sample consisted of young and older adults who were of normal weight, physically active, cognitively normal, and did not have any major medical conditions that prohibited their exercise engagement. Even though it was planned to recruit physically active individuals for the current study to ensure that exercise could be completed safely, and that participants would be physically capable of exercising for 20 minutes at moderate-to-vigorous intensity, this is a limitation. Little research has been done utilizing a sample of sedentary individuals who complete an acute bout of aerobic exercise which makes it hard to speculate how the relatively high physically activity levels of this sample could have influenced the results. These physically active participants could respond more positively to the acute bout of aerobic exercise because they are used to the stress that the bouts require. If a similar study were done on a sample of sedentary individuals a lower exercise intensity would most likely need to be utilized to ensure participants could finish the exercise bout without becoming overly fatigued. There was also a significant condition x age group interaction for HRR% such that older adults had significantly higher HRR% during the exercise bout compared to the young adults (58.1% vs. 59.8%). While this difference is only 1.7%, it could have potentially impacted the results such that the older adults had greater arousal following the bout which could be related to the significantly greater improvements they showed on memory performance compared to the young adults. The sample was healthy, physically active young and older adults, which may limit the generalizability of the findings. Future research should be conducted examining how a single bout of aerobic exercise impacts cognitive functioning in sedentary individuals who do not have experience exercising and could potentially stand to gain greater benefits than an individual who already chronically exercises.

Conclusion

These findings present evidence that aging moderates the relationship between an acute bout of aerobic exercise and cognitive functioning. Exercise had a significant effect on select aspects episodic memory and executive function in both age groups, and for certain outcome variables, older adults benefited more greatly compared to the young adults. For episodic memory, we found that for both age groups exercise had an enhancing effect on performance. Post-hoc analyses showed that during the control condition, there were significant differences between young and older adults on trials 1 – 5, trial 7, and delayed recall such that older adults recalled fewer words. These significant differences were no longer present following the exercise condition potentially indicating that the older adults benefited enough from the single bout of aerobic exercise that their performance no longer significantly differed from that of the young adults.

For the Stroop task, we found that for both age groups, completing a 20-min bout of aerobic exercise resulted in participants having less of an interference effect on their accuracy at performing the Stroop task compared to the control condition. There was also no evidence that the older adults gained greater benefits from an acute bout of aerobic exercise in terms of Stroop performance. For spatial working memory performance, there was a significant condition effect for accuracy level 2 such that for both age groups, completing a 20-min bout of aerobic exercise resulted in participants responding more accurately when they had to process two dots in comparison to performance following the control condition. Finally, we found that during the control condition, there were significant differences between young and older adults in terms of their accuracy during level 4. During the exercise condition there were no longer significant differences between the young and older adults on their accuracy during level 4.

As discussed above, previous meta-analyses have shown benefits following acute exercise on both memory (Roig et al., 2013) and executive function (Chang et al., 2012; Lambourne & Tomporowski, 2010; Ludyga et al., 2016) performance. Despite that, the benefits for executive functioning tend to be small in magnitude, and the number of studies conducted examining how older adults’ memory might benefit from acute exercise are extremely low.

The current findings suggest that while both young and older adults can benefit cognitively from a single bout of aerobic exercise, older adults’ stand to gain more. Future research needs to examine how an accumulation of these acute bouts of exercise lead to chronic changes in cognitive functioning as we age. In addition, other moderators need to be examined such as sex, physical activity level, or genetics so individual factors can be accounted for when prescribing exercise for the ever-growing population of older adults. Studies such as these will help educate groups of people that respond to exercise in varying ways, as well as identify individual factors that interventions should target to improve the outcomes.

General discussion

With the current methods it was possible examine how aging impacts the exercise – cognition relationship like what has been previously done in cognitive psychology. The main purposes of study 1 were to examine if the sample of healthy, cognitively normal older and younger adults have significant differences in their cognitive abilities without any treatment, and to examine if older adults who are more physically active perform better on the cognitive tasks assessing episodic memory, associative memory, and executive functioning. The main purposes of study 2 were to examine how a single bout of moderate intensity aerobic exercise impacts episodic memory and executive functioning in both young and older adults.

The results of study 1 are mixed. It was found that across a majority of the outcomes that age group was a significant negative predictor of performance showing that aging has a significant deficit effect on various aspects of cognitive functioning. For some of the outcomes, it was also found that physical activity engagement is related to cognitive functioning for both age groups, with some showing that older adults had a stronger positive relationship between physical activity engagement and cognitive functioning, and some outcomes showing that young adults showed a stronger relationship between physical activity engagement and cognitive functioning. Despite the mixed results, they are promising. Using an easily utilized subjective measure of physical activity engagement, it was found that for older adults, young adults, and in some cases both age groups, physical activity engagement was positively associated with performance on tasks assessing episodic memory and executive functioning. The current study appears to have been underpowered to fully detect significant differences on tasks assessing executive functioning, but we believe we have added valuable information for future researchers to use and build from.

The results of study 2 are clearer than those of study 1. For RAVLT performance, exercise had a significant enhancing effect on the number of words recalled across both age groups compared to the control condition across all outcomes (trial 1, trials 1 – 5, trial 7, following a delay). Even more important, it was also found that for trials 1 – 5, trial 7, and delayed recall there were significant condition x age group interactions. Across outcomes the results consistently showed that during the control condition there were significant differences between the young and older adults' performance. Following the exercise condition, performance between the young and older adults were no longer significantly different. While both age groups did significantly improve following the exercise condition, the older adults improved enough to no longer significantly differ in the number of words recalled across multiple trials of the RAVLT and following a delay. For single-item episodic memory, the results would indicate that at least temporarily, an acute bout of aerobic exercise can enhance older adults' memory enough to perform similarly to healthy, physically active, young adults. It should be noted that these effects are temporary and not enough research has been conducted for us to know how long the beneficial effects related to RAVLT performance would last.

In terms of executive functioning, results showed that for Stroop accuracy interference and spatial working memory accuracy for set size 2 there were significant condition effects such that exercise had an enhancing effect to decrease interference scores for Stroop accuracy, and greater accuracy for the spatial working memory task for set size 2. There were no other significant enhancements following exercise for executive function outcomes. The interaction showed that young adults had no significant differences between the exercise and control condition while the older adults had significant improvements in their accuracy at the most difficult aspect of the spatial working memory task following the exercise condition. With no significant differences for Stroop reaction time, and working memory reaction time, these results could show that enhancements in executive functioning manifested as improvements in accurately processing stimuli and responding at a consistent rate.

Across all our outcomes we have shown that a single bout of aerobic exercise can have enhancing effects on STM (RAVLT), LTM (RAVLT), inhibition (Stroop task), and select aspects of spatial working memory. These effects were not exclusive to the older adults but also occurred in the young adults as well. We have also shown that older adults do indeed stand to gain more benefit from a single bout of aerobic exercise in terms of their episodic memory performance, and their ability to retain spatial information and manipulate remembered items in working memory. Despite the very compelling findings found across these two studies, there are still many gaps in our knowledge that future research needs to address. With the ever-growing population of older adults, having a greater understanding of the types of cognitive domains that are related to physical activity engagement, or the types of exercise bouts individuals should be engaging in everyday to accumulate cognitive benefits are vital. More information on these topics is needed so practitioners can build better exercise prescriptions to help slow the rate of ARCD and improve the quality of life of the elderly.

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APPENDIX A: STUDY 1 PHYSICAL ACTIVITY INFORMATION

	Young adults (n = 28)	Older adults (n = 26)
Total Physical Activity level (Met-mins/week)	3661 ± 3120	1870 ± 2843
Vigorous work activity (Met-mins/week)	522 ± 1451	129 ± 500
Moderate work activity (Met-mins/week)	619 ± 1447	377 ± 1003
Transportation activity (Met-mins/week)	590 ± 591	233 ± 540
Vigorous leisure activity (Met-mins/week)	1373 ± 1369	472 ± 832^
Moderate leisure activity (Met-mins/week)	556 ± 452	658 ± 1602
Average sedentary time per day (mins)	381.4 ± 134.9	496.2 ± 184.6

Note. Standard deviations are presented with means.