Investigating the Effect of High-Intensity Aerobic Exercise on Executive Functions: A Scoping Review

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ABSTRACT

High intensity (HI) aerobic exercise is considered to be a time-efficient strategy for improving executive functions (EF). EFs include attention, cognitive flexibility, working memory, and inhibition, and are important for healthy mental functioning. To date, the literature examining the efficacy of HI exercise for improving EF is mixed, with the understanding that at a too high of an intensity, EF suffers. We therefore designed a scoping review to reveal the general consensus of the current body of literature. We systematically reviewed research studies that behaviourally measured EFs before and after a bout of HI aerobic exercise. We found that there is no clear support for the ability of HI aerobic exercise to improve or hinder EFs. We also showed the lack of definitive results was likely due to the heterogeneity across study designs. Our findings highlight the need to establish thorough standardization of exercise and cognitive methodologies and measurements.

LIST OF ABBREVIATIONS USED

ACSM: American College of Sports Medicine

ADHD: Attention Deficit Hyperactive Disorder

aMCI: Amnestic Mild Cognitive Impairment

AT: Anaerobic Threshold

BDI: Beck Depression Inventory

BDNF: Brain Derived Neurotrophic Factor

BL: Blood Lactate

CCPT: Conner's Continuous Performance Task

CCP: Contingent Continuous Performance

CRH: Corticotropin-Releasing Hormone

DSM-IV: Diagnostic and Statistical Manual of Mental Disorders, 5th Edition

fMRI: Functional magnetic resonance imaging

GET: Gas Exchange Threshold

GMXT: Graded Maximal Exercise Test

GR: Glucocorticoid Receptors

HGF: Hepatocyte Growth Factor

HI: High Intensity

HIIT: High intensity Interval Training

HR: Heart rate

HRR: Heart Rate Reserve

IQ: Intelligence Quotient

KBIT: Kaufman Brief Intelligence Test

LI: Low-intensity

LT: Lactate Threshold

MDD: Major Depressive Disorder

MI: Moderate-intensity

MICE: Moderate Intensity Continuous Exercise

MMSE: Mini-mental State Examination

MoCA: Montreal Cognitive Assessment

MWT-B: Multiple Choice Vocabulary Test Version B

NGF: Nerve Growth Factor

OCPD: Obsessive Compulsive Personality Disorder

PAR-Q: Physical Activity Readiness Questionnaire

PFC: Prefrontal Cortex

Pmax: Power Max

PPO: Peak Power Output

RPE: Rate Perceived Exertion

PRESS: Peer Review Electronic Search Strategies

PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-analysis

PTSD: Post Traumatic Stress Disorder

PvT2: power at Ventilatory Threshold 2

ROS: Reactive Oxygen Species

RT: Reaction Time

SCID-I: Structural Clinical Interview for DSM-IV

TMT: Trail Making Test

ToH: Tower of Hanoi

VEGF: Vascular Endothelial Growth Factor

VT: Ventilatory Threshold

VTA: Ventral Tegmental Area

WCST: Wisconsin Card Sorting Task

WMC: Working Memory Capacity

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Chapter 1: Introduction

1.1 Initial Summary

Cognition can be defined as the collection of processes involved in the acquisition, storage, transformation, and use of knowledge (Matlin, Cognition 8th edition). Throughout history, humans have noted the connection between head trauma and behavioural changes but the modern notion of cognitive neuroscience didn't develop roots until the 1800's when early scientists began assigning functions to brain regions based on how behaviours change after injury. Over the course of the next several centuries, cases such as those of Phineas Gage and Henry Molaison have helped psychologists and neuroscientists understand which areas of the brain correspond to specific cognitive functions.

One area of the brain that has been the focus of much research is the prefrontal cortex (PFC), the region encompassing the anterior surface of the frontal lobe. The PFC is most notably responsible for higher order cognitive processes such as self-monitoring and personality expression. It is also the region responsible for coordinating and housing a set of crucial mental functions known as *executive functions* (Yuan & Raz, 2014).

Executive functions (EF) can be understood as sets of top-down control processes and mental abilities needed when routine behaviours, thoughts, and/or emotions are insufficient to handle the task at hand (Diamond, 2013). Research over the past 20 years has linked EF to countless aspects of well-being and life. Executive functions are impaired in many mental disorders such as attention deficit hyperactive disorder (ADHD; Diamond, 2005; Lui & Tannock, 2007), depression (Taylor-Travares et al., 2007), and

schizophrenia (Barch, 2005). Impaired EF has also been associated with impaired productivity at work and difficulty finding and keeping employment (Bailey, 2007). It also impacts success in school (Borella et al., 2010; Duncan et al., 2007; Gathercole et al., 2004), quality of life (Brown & Landgraf, 2010; Davis et al., 2010), and even physical health (Crescioni et al., 2011; Miller et al., 2011; Riggs et al., 2010). In their 2015 report, the mental health coordinating council (MHCC, 2015) details the link between cognitive deficits and mental health, and that often the cognitive deficits can go untreated which can further impair mental health and function. At the time of writing this paper, there has also been a dramatic drop in the mental health of Canadians due to the isolation, fear, and instability caused by the COVID-19 pandemic (Best et al., 2021; Gadermann et al., 2021; Nwachukwu et al., 2020). While many of the factors contributing to this global shift in mental health are beyond the scope of this paper, there are potential coping strategies that can be explored. Fortunately, there is a known intervention with a robust and vast amount of evidence in favour of its beneficial effects on the brain and body: aerobic exercise.

Aerobic exercise is any activity that conditions and challenges the cardiovascular system. Besides increased blood flow and heart rate (HR), aerobic exercise creates other changes in the body and brain. Numerous studies have illustrated the benefits of aerobic exercise in promoting plasticity in the brain (Singh et al., 2014; Smith et al., 2014; Mooney et al., 2016) and recovery after injury such as stroke or concussion (Murdoch, Buckley, & McDonnell, 2016; Vanderbeken & Kerchhofs, 2017). Aerobic exercise has also been shown, in animal models, to prevent stress related damage to cortical areas (Chen et al., 2017). However, as training techniques change and evolve, this raises the

question as to whether there is an optimal aerobic exercise protocol or approach that most benefits cognitive function. The majority of literature has focused on moderate intensity continuous exercise (MICE) protocols.

According to the American College of Sports Medicine (ACSM)'s guidelines, moderate-intensity aerobic exercise is defined as being between 43-63% VO2max and/or between 64-76% HRmax. In MICE protocols, participants perform aerobic exercise at a moderate intensity that is maintained for a pre-determined duration, usually 20 – 40 min (for a meta-analysis see Ludyga, Gerber, Brand, Holsboer-Trachsler, & Puehse, 2016). More recently, an alternative aerobic exercise protocol has gained interest: high intensity (HI) exercise. HI aerobic exercise ranges between 64-90% VO2max and/or 77-95% HRmax, and, in comparison to MICE, has been suggested to be a more time efficient method of obtaining aerobic exercise-induced cognitive benefits (Kao et al., 2018). Since HI protocols challenge the cardiovascular system to such a high degree, they are rarely continuous and are more often divided up into intervals, as is the case in high intensity interval training (HIIT) which involves alternating short bouts (1 – 4 mins) of HI exercise with moderate or low-intensity intervals. Additionally, acute exercise paradigms offer a unique advantage by acting like a snapshot into the brain and body. A review by Basso & Suzuki (2017) discussed how just a single acute session of aerobic exercise can induce changes in the brain that can be measured on a behavioural/cognitive level and a neurophysiological/functional level. Since chronic exercise paradigms are technically a repetition of acute exercise, looking at a single acute session could provide novel insights to what occurs in the long term.

However, other than the time benefits, there is still much debate about whether

acute HI exercise can provide the same level of cognitive benefits as MICE. As such, the purpose of this scoping review is to assess the available literature for emerging trends between acute HI exercise and EF.

1.2 Background and Rationale

1.2.1 Executive Functions

As a whole, EFs are considered higher order cognitive functions as they are effortful, in contrast to passive, like certain types of memory formation. They are intentional, goal-directed, motivation-driven, and are essential for success in industrialized society. However, EFs are not a single, unified process. Just as the term 'cognition' can be broken down into numerous sub-categories and concepts, the same can be said for EFs.

In general, there are four core components that make up EFs: inhibitory control, working memory, attention, and cognitive flexibility. While numerous brain regions are involved with EFs, the frontal lobes and PFC are where these processes intersect through neural connections across the various sub-regions. For the current study, attention, inhibition, working memory, and cognitive flexibility will be explored. Below, each of these processes will be explained in further detail in addition to methods by which these functions are measured, and the disorders that arise when they are impaired.

1.2.1.1 Attention.

Attention can be defined as the concentration of mental activity that allows one to focus on and take in a limited amount of information from the unlimited material that comes from our senses and memories (Matlin, Cognition, 8th edition, 72-73). Attention is

intrinsically linked to long-term memory, problem solving and language processing. Attention is often studied in the context of school and academic performance, and indeed, children that rate higher on the Attention Control Scale for Children (a 20-item self-rating scale used to assess ability to focus and shift attention) show a positive correlation with school performance (Muris, 2006). In children with ADHD, there is a direct link between severity of behavioural symptomatology and academic performance with greater severity resulting in worse school performance (Barry, Lyman, & Klinger, 2002).

In adults, poor attention is associated with reduced productivity at work. For example, employees with ADHD would sooner respond to a low priority email that gives immediate sense of completion rather than work on a larger, high priority task that will not give immediate reward (Bozionelos & Bozionelos, 2013). Children and adolescents with ADHD also have high co-morbidity with depressive disorder with co-occurrence happening in 15-75% of cases (for reviews see Biederman, Newcorn, & Sprich, 1991; Spencer, 2006; Spencer, Biederman, & Mick, 2007) and the risk of children with ADHD developing depressive disorder is 5.5 times higher than in children without ADHD (Angold, Costello, & Erkanli, 1999). In a recent paper, investigators conducted a 7 year longitudinal study in a group of children to determine the connection between individual differences in attentional control and risk for depression during adolescence (Rudolph, Monti, & Flynn, 2018). It was found that in girls, but not boys, attentional control deficits are a predictor of heightened stress reactivity which increases the risk of depression. The cognitive inflexibility and inability to shift attention may be at the core of this heightened sensitivity as adolescents remained focused on the stressful event and cannot remove themselves from the negative thoughts and feelings (Miyake, 2000; Compas et al., 2004).

Attention also works in conjunction with working memory as part of the central executive which acts to integrate all components of working memory as well as focus attention, select strategies, transform information, and coordinate behaviour (Baddeley, Hitch, & Allen, 2009). It is also the central executive that is at work when one daydreams, and early studies showed that the amount of resources used during daydreaming is enough to impair performance on the random-number generation task, a task which relies heavily on the central executive (Teasdale et al., 1995). This has important implications when considering tasks that require constant vigilance, such as driving. A recent study in young men (aged 18-21) showed a connection between mind wandering tendency and risky driving (Albert et al., 2018) while other studies have also shown mind wandering with high disturbing thought content to be a significant risk factor for road traffic crashes (Lagarde, Gabaude, Maury, Lemercier, Salmi, & Galéra, 2012).

1.2.1.2 Inhibition.

In general, the process of inhibition can be summarized as our ability to selectively ignore unessential information or stimuli, or in other words, prevent our attention from wandering. This type of inhibition is termed *cognitive inhibition* or *interference control* and involves the suppression of extraneous or unwanted stimuli that comes from within our own minds such as intentional forgetting (Anderson & Levy, 2009), inhibiting interference from old information, and inhibiting interference from newly learned information (Postle et al., 2004). It is this process that enables one to stay on-task despite the impulsive urges to do otherwise. Deficits in cognitive inhibition have been linked to symptoms of ADHD and Autism Spectrum Disorder. One study that looked at children with high functioning autism and ADHD found that, during the no-go

trials of a Go/No-Go task, these children took longer to respond and had reduced activation in the PFC as compared to typically developing children (Xiao et al., 2012). In the Go/No-go task used by Xiao et al (2012), participants were presented with two different trial types: Go trial, and No-go trial. In the no-go trial, two different stimuli were presented ("X" and "O") and the participants were instructed to respond when "O" was presented, but to withhold a response when "X" was shown. The ability of the participant to withhold their response was a measure of inhibitory control.

A similar test to the Go/No-Go task is the Stop-signal reaction time task that measures the time it takes to stop an already initiated response. Participants are told to respond as quickly as possible to a stimulus presented on a screen, but then must inhibit this response when a second stimulus (e.g., a beep or a symbol) is presented before the normal "respond" stimulus (Coulacoglou & Saklofske, 2017). In patients with schizophrenia it was found that, compared to controls, they had a slower Stop-signal reaction time and reduced activation in the right inferior frontal gyrus (Hughes et al., 2012), an area associated with inhibition, attention, and social cognition (Hartwigsen et al., 2019). Patients with schizophrenia also show impairment on a cognitive test known as the Stroop test (described below) in which they exhibit increases in reaction time and decreased accuracy (Westerhausen, Kompus, & Hugdahl, 2011).

The Stroop color-word interference test is an assessment that challenges inhibitory processes (Stroop, 1992). Typical versions of the task require participants to read off a list of 4 alternating words that can either be "GREEN", "RED", "BLUE", or "YELLOW". In congruent trials, the word will be printed using the same colour as their meaning (e.g. BLUE will be written with blue ink). The interference trials, however, are

incongruent such that the words are written in a colour that is inconsistent with their meaning (e.g. BLUE will be written in red). This incongruence provides a classic scenario of inhibiting the automatic process of reading the word in order to focus on the colour of the text. The amount of interference, also called the Stroop Effect, is measured by how long it takes participants to complete the list of words and the number of errors made. A larger Stroop Effect infers weaker inhibitory abilities or performance.

Interestingly, modified versions of the Stroop have been developed to investigate emotional vulnerability and aggression. In the emotional Stroop task, participants must once again name the colours of the words presented, but instead of the words themselves being colours, the words can either be neutral or emotionally charge (e.g., death, cancer, kill). In this case, the Stroop Effect is the speed at which the participant names the colour of the emotionally charged word (Gotlib & McCann, 1984; Williams, Mathews, & MacLeod, 1996).

A recent meta-analysis examining post-traumatic stress disorder (PTSD), major depressive disorder (MDD), and anxiety disorder, found that individuals with PTSD exhibit greater interference for diagnosis-related stimuli and positive stimuli, but not for generally negative stimuli whereas those with MDD and anxiety disorder showed high interference to diagnosis-related and negative stimuli, but not positive stimuli (Joyal et al., 2019). This finding was attributed to the notion that cognitive inhibition is also implemented in the control of emotions and mood regulation, and further that there is a strong link between depression and inhibition dysfunction, whereby individuals with depression are unable to inhibit negative thoughts or expel them, leading to the rehearsal and rumination of negative thoughts (Joormann, 2010). Furthermore, the greater the

deficit in cognitive inhibition, the more at risk depressive individuals become to suicide attempts (Richard-Devabtoy et al., 2015). This is particularly important in older populations as inhibitory control is extremely sensitive to decline with age (Hasher & Zacks, 1988; Hasher et al., 1991), and in depressed elderly populations, it is considered a neurocognitive marker for those individuals found to be at high-risk for attempting suicide (Richard-Devantoy et al., 2012; Richard-Devantoy et al., 2014).

Another dimension of inhibitory control is our ability to inhibit reflexive, impulsive, and habitual actions and is termed *response inhibition*. Impulsivity, or impaired response inhibition, is at the core of many substance abuse disorders (Zilverstrand et al., 2018; Byrne & Worthy, 2019), eating disorders (Schmidt et al., 2012; Svaldi et al., 2015), and is associated with mental disorders such as schizophrenia (Wykes, 1996; Enticott et al., 2008; Kaladjian et al., 2011).

These two forms of inhibition (i.e., cognitive inhibition and response inhibition) work together seamlessly to prevent lapses of self-control and impulsive decision making. As discussed above, when these processes are impaired this can lead to difficulties in managing day-to-day activities and social interactions at best, and harmful behaviour at worst.

1.2.1.3 Cognitive flexibility.

Cognitive flexibility is the ability to change our perceptions and viewpoints, adapting to the task at hand by flexibly shifting the rules, and adjusting our priorities as needed. Challenges that require one to expand the solution beyond what is obvious or

straightforward (or in other words, problem solving) make use of cognitive flexibility, and the more flexible one's thoughts are, the more creative and diverse the solutions.

Cognitive flexibility is not just limited to problem solving; it also feeds into the complexity of our thoughts and how well we can shape them when they become harmful or maladaptive. For example, patients diagnosed with anorexia nervosa have cognitive deficits regarding their bodies such that their perception of themselves is distorted. Patients with anorexia nervosa score lower on the Wisconsin Card Sorting Task (WCST) than healthy controls and show different levels of brain activation (Sato et al., 2013). Using functional magnetic resonance imaging (fMRI) it was found that, while completing the WCST, those with anorexia nervosa had lower activity in the ventrolateral PFC and bilateral parahippocampal cortex, two regions of importance for set-shifting which, along with task-switching, is a measure of cognitive flexibility (Ravizza & Carter, 2008; Sato et al., 2013).

In fact, impaired cognitive flexibility is considered a risk factor for development of anorexia nervosa (Steinglass, Walsh, & Stern, 2006; Tchanturia, Campbell, Morris, & Treasure, 2005). It is believed that impaired flexibility leads to rumination of distorted thinking and therefore maintenance of symptoms (Steinglass et al., 2006; Schmidt & Treasure, 2006). Impaired cognitive flexibility is also a characteristic of cocaine and gambling addictions with both disorders exhibiting decreased activation in the ventrolateral (Verdejo-Garcia et al., 2015) and ventromedial PFC (Leeman & Potenza, 2012) as measured by fMRI.

Obsessive-compulsive personality disorder (OCPD) is an early-onset disorder characterized by perfectionism, need for control, as well as cognitive rigidity (Butcher, Mineka, & Hooley, 2010), and individuals with the disorder show impaired performance on measures of cognitive flexibility and executive planning (Fineberg et al., 2015). As alluded to above, while each EF is distinct, their overlapping properties allow for specific behaviours and cognitive abilities. Similar to the maladaptive behaviours found in OCPD, when attention is impaired individuals can experience difficulty drawing their attention away from harmful ideas. Their thoughts become inflexible and rigid, similarly to when cognitive flexibility is impaired.

While it is impossible for any single test or task to rely on only one EF, for cognitive flexibility, tasks that require one to switch fluidly between concepts, rules, or ideas are the most effective. One of the oldest tests for assessing cognitive flexibility is the WCST (Milner, 1964; Stuss et al., 2000), where participants are required to sort cards based on an initial criterion (i.e., by colour, shape, number). Participants are uninformed on what this rule is and must learn it as quickly as possible based on the feedback they receive (correct placement or incorrect). Once the rule is figured out and the participant no longer makes any errors, the rule is changed. Changing the 'rules' in this way throughout the test forces participants to update and switch their modes of thought as required, thus providing an indication of cognitive flexibility.

Modified versions of the Stroop task can also be used to assess cognitive flexibility. In the computerized Stroop task developed by Laguë-Beauvais and co-authors (2013), participants must switch back and forth between reading the word and reading the colour of the word on each trial. This is an example of task-switching, a type of mental

activity where individuals must switch between tasks with different sets of instructions when presented with a specific stimulus (Dajani & Uddin, 2015). Task-switching is often a key feature in tests of cognitive flexibility as it requires one to adapt and react flexibly to changes in the environment (Miller & Cohen, 2001; Armbruster, Ueltzhöffer, Basten, & Fiebach, 2012).

In their original study Laguë-Beauvais et al (2013) showed, in healthy young adults, that during the switching component of the computerized Stroop there was an increased activation of several sub-regions within the PFC (left dorsolateral and ventrolateral) critical for task-switching (Brass & von Cramon, 2002; Derrfuss et al., 2005; DiGirolamo et al., 2001; Dove et al., 2000; Hampshire and Owen, 2006; Wylie et al., 2004; Yeung et al., 2006). These regions are also recruited when participants perform the WCST (Monchi, Petrides, Petre, Worsley, & Dagher, 2001; Ko, Monchi, Ptito, Petrides, & Strafella, 2008).

1.2.1.4 Working Memory.

Working memory is likely the most complicated of the EFs as it has its own multi-component system involved in holding onto the information that we are currently manipulating (Diamonds, 2013). Working memory is distinct from short-term memory as its function is not to temporarily encode information but rather to keep it active and changeable for the duration of time required. According to Baddeley's model (2000), working memory comprises four systems: the phonological loop, the episodic buffer, the visuo-spatial sketchpad, and the central executive. In brief, the phonological loop rehearses vocal and subvocal information, such as lists of words or numbers; the visuospatial sketchpad stores visual and spatial information to recreate a three-

dimensional physical environment in the mind for manipulation; the episodic buffer holds information from both working memory and long term memory together in a limited capacity; and finally, the central executive focuses and splits attention, switches between tasks, pulls information from long term memory, and integrates the other components together.

Working memory is no doubt the most diverse and complex of the EFs, as such, it is both a director of attention, inhibition, and cognitive flexibility, but also depends on them to function properly. For example, numerous studies have illustrated that working memory capacity (WMC), the amount of information we are able to store and manipulate at a given time, is modulated by attention (Unsworth & Robison, 2018). A series of studies conducted by Eagle, Kane, Conway, and colleagues has suggested that individual differences in WMC are strongly modulated by attentional control (Engle & Kane, 2004; Kane & Engle, 2002; Kane et al., 2007). Indeed, WMC differences have been demonstrated in numerous vigilance and attention-dependent tasks such as dichotic listening (Colflesh & Conway, 2007; Conway, Cowan, & Bunting, 2001), Stroop interference (Hutchison, 2011; Kane & Engle, 2003; Long & Prat, 2002; Meier & Kane, 2013; Morey et al., 2012), flanker interference (Heitz & Engle, 2007; Redick & Engle, 2006), performance on the antisaccade task (Kane et al., 2001; Unsworth, Schrock, & Engle, 2004), and performance on versions of go/no-go tasks (Redick et al., 2011).

It is thought that this connection between attentional control and WMC capacity is related to attention-based ability to maintain task goals in the presence of distraction (Unsworth & Robison, 2018). When attention is strained with unnecessary details and

conflicting goals, this in turn disrupts the ability of the central executive to focus resources, thus limiting the WMC and cognitive performance. Unsurprisingly, both children (Martinussen, Hayden, Hogg-Johnson, & Tannock, 2005) and adults (for review see Alderson et al., 2013) with ADHD and individuals with schizophrenia (Kuperberg & Heckers, 2000; Lett et al., 2014) have been shown to have deficits in working memory.

Inhibitory control also plays a major role in working memory. As mentioned before, mind-wandering tendencies are important in successful execution of various daily tasks. Preventing mind-wandering requires attention and inhibition. In one study of 124 undergraduate students, participants were given a working memory-based task before commencing a week-long self-report protocol to monitor mind-wandering (Kane et al., 2007). It was found that those with higher WMC were better able to remain on-task and inhibit distractions. In this sense, it is thought that better inhibitory control allows the working memory space to remain "uncluttered".

An uncluttered and well-functioning working memory is important for both mental and emotional health across the lifespan. Individuals with anxiety often show deficits in working memory capacity as the anxiety-related thoughts compete with the task-specific processes. A meta-analysis of 177 studies revealed that self-reported measures of anxiety are reliably related to poorer performance on tasks of working memory capacity (Moran, 2016). One study has also provided evidence that gender disparities in math are linked to heightened worry in women, therefore taxing the visuospatial working memory resources needed to perform the task (Ganley & Vasilyeva, 2014). In children, a link between child-hood obesity and poor academic performance has been thought to be due to deficits in working memory exhibited by over-weight and

obese children (Wu, Chen, Yang, & Li, 2017). Working memory has also been shown to be important in forming teacher and peer social relationships in elementary-school aged children (De Wilde, Koot, & van Lier, 2016).

1.2.2 Cognition and Aerobic Exercise.

In general, the literature has suggested a strong link between aerobic exercise and cognition. The Tower of London task is a cognitive test that measures one's ability to plan and inhibit reckless decision making. In one study, participants completed the Tower of London task four times: prior to, immediately following, 30 min after, and 60 min after cessation of a 30 min bout of moderate intensity (60-70% HR reserve, HRR) cycling exercise (Hung, Tsai, Chen, Wang, & Chang, 2013). It was found that, immediately following the aerobic exercise, the participants required fewer moves in total to complete the task compared to non-exercise controls. Furthermore, 30 and 60 min after the protocol, those that underwent aerobic exercise had longer initiation times, meaning they didn't impulsively jump to begin the task and thought about it longer before beginning. This study illustrated that an acute bout of aerobic exercise can enhance the planning and inhibitory aspects of EF. Long term aerobic exercise regimes can also enhance cognition. In another study, participants underwent a 10 week aerobic exercise training regime using three different groups that were exposed to different intensity levels: the control group participated in aerobic exercise 0 – 2 days/week, the moderate activity group did 3 – 4 days/week, and the high activity group exercised 5 – 7 days/week (Masley, Roetzheim, & Gualtieri, 2009). It was found that the more frequently the participants engaged in aerobic exercise, the better they performed on measures of cognitive flexibility, as assessed by the CNS Vital Signs® computerized cognitive battery.

Furthermore, engaging in at least moderate intensity aerobic exercise training (≥45 min per session as frequently as possible) is an effective way to prevent cognitive decline associated with age (Northey, Cherbuin, Pumpa, Smee, & Rattray, 2017). Higher cardiovascular fitness is also associated with greater cerebrovascular function in older adult women, which was a predictor of cognitive function (Brown et al., 2010). Longitudinal studies support this neuroprotective effect of aerobic exercise on age by showing positive correlations between cardiovascular fitness and global cognitive function in older adults (Barnes, Yaffe, Satariano, & Tager., 2003; Weuve, Kang, Manson, Breteler, Ware, & Grodstein, 2004).

These findings are consistent across the literature of exercise and cognition (for reviews see Swain et al., 2012; Hötting & Röder, 2013) and numerous studies have investigated the origin of this connection. One of the most well documented aerobic exercise-induced changes in the brain is that of neuroplasticity and neurogenesis. Neuroplasticity is the process of reforming and reshaping synaptic connections based on experience and learning while neurogenesis is the related process of growing new neurons. Both of these processes are highly active during development, with a decreased rate in adulthood. Areas of the adult brain that persist in growing new neurons are located in the hippocampus, an area responsible for learning and memory, and the olfactory bulb. While aerobic exercise has been shown to enhance neurogenesis, these changes have been limited to the hippocampus, but that doesn't mean the benefits of aerobic exercise stop there as well.

In contrast to the limited brain regions that support neurogenesis, aerobic exercise-induced changes in plasticity can occur in various regions of the brain. A single

bout of aerobic exercise has been shown to enhance plasticity in the primary motor cortex (Singh et al., 2014; Smith et al., 2014; Mooney et al., 2016; MacDonald, Khan, Kraeutner, Usai, Roger, Kimmerly et al., 2019) and more recent research is beginning to show changes in frontal lobe regions. In adults with amnestic mild cognitive impairment (aMCI), 6 months of aerobic exercise training via treadmill (at 70 – 80% HRR) resulted in significantly enhanced functional connectivity in the PFC, whereas the stretching control group had no changes (Hugenschmidt et al., 2017). The same group of researchers also established that 6 months of aerobic exercise improves performance of EF in adults with aMCI (Sachs et al., 2016). Indeed, chronic aerobic exercise has been shown to enhance and strengthen functional connectivity of the PFC in older adults, thus preventing normal cognitive decline with age with particular protective effects placed on EFs (for reviews see Kramer & Erickson, 2007; Erickson & Kramer, 2009; Voss et al., 2010). The proposed mechanisms by which aerobic exercise enhances connectivity within the PFC and with other areas of the brain have been explored using acute bouts of aerobic exercise.

A study using both healthy younger and older adult participants found that 30 min of moderate-intensity aerobic exercise (cycling at 65% of HRmax) increased synchrony in networks involved in learning and memory, executive control, attention, and reward processing (Weng et al., 2017). The authors stipulate that these changes, when occurring over a period of weeks and months as they would with a long term aerobic exercise training routine, would result in increased functional connectivity. In terms of cognition, resting state functional connectivity in the frontoparietal control network has been shown to be significantly associated with performance on tasks of EF in older adults (Shaw,

Schultz, Sperling, & Hedden, 2015). Considering that functional connectivity declines with age (Ferreira & Busatto, 2013; Voss et al., 2013), the findings of Weng and co-authors (2017) show that aerobic exercise could be used as a long-term intervention to mitigate age-related declines in EFs.

Other cellular mechanisms that contribute to the association of AE and cognitive performance are exercise-induced angiogenesis. Angiogenesis is the sprouting of new blood vessels from pre-existing capillaries; studies applying aerobic exercise-based training in mice have shown increased blood flow, vascular density, and angiogenesis in areas such as the hippocampus, primary motor cortex, and cerebellum (Nishijima & Soya, 2006; Sikorski & Swain, 2006; Kerr & Swain, 2011). In humans, life-long aerobic exercise has been shown to preserve blood supply in the brain's default-mode-network that usually declines with age (Thomas et al., 2013). Increased cerebrovasculature has also been suggested to be a linking factor for aerobic exercise-induced improvements in cognition in healthy young populations (Guiney, Lucas, Cotter, & Machado, 2015).

Angiogensis, neurogenesis, and neuroplasticity are all cellular processes that aerobic exercise can alter to enhance cognition, but they are not the only level of aerobic exercise-induced modification. On a molecular level, aerobic exercise can enhance the production and proliferation of growth factors that maintain general health of the brain by promoting growth and survival of neurons. Change in the concentration or expression of these growth factors are also the driving force behind the cellular and system wide changes seen after aerobic exercise. Some growth factors and receptors that are known to respond to exercise include vascular endothelial growth factor (VEGF), brain-derived

neurotrophic factor (BDNF), and nerve growth factor (NGF; Neeper et al., 1996; Ding et al., 2004; Zhu et al., 2006).

VEGF is found throughout the body including expression in the brain and is up-regulated in animal models of exercise, leading to increased blood vessel density in areas such as the striatum and cortex (Sun et al., 2003; Ding et al., 2004; Ding et al., 2006; Tang, Xia, Wagner, & Breen, 2010). Furthermore, exercise-induced neurogenesis is dependent on the activity of VEGF in the peripheral nervous system (Fabel et al., 2003). By blocking peripherally produced VEFG, Fabel and colleagues were able to abolish exercise-induced hippocampus neurogenesis in rats.

Another important growth factor that has accumulated a large body of research in the area of exercise and cognition is BDNF. In general, BDNF is crucial for neurogenesis and neuroplasticity in the brain as it promotes neuron survival by stimulating neuronal growth, maturation, and maintenance. In humans and animal models, exercise has been shown to increase levels of BDNF (Neeper et al., 1995; Radak et al., 2006; Gomez-Pinilla, Vaynman, & Ying, 2008; Marais, Stein, & Daniels, 2009; Rasmussen et al., 2009) following an acute bout of exercise. For example, blood samples were taken from the radial artery and internal jugular vein of human participants before and during a 4 h rowing exercise session (Rasmussen et al., 2009). It was found that during exercise, the BDNF levels in the brain increased two- to threefold. In the same study, mice that were exercised for 2 hours on a treadmill showed a three- to fivefold increase in BDNF expression in the hippocampi and cortex that peaked 2 hours post-exercise.

The beneficial actions of BDNF are also shown in long-term aerobic exercise training. Neeper and colleagues (1996) gave rats access to a running wheel for two, four, or seven nights and found a significant increase in BDNF mRNA levels, a measure of BDNF expression, in exercised rats compared to controls. The link of BDNF with cognitive performance comes from studies showing increased serum BDNF concentrations to be associated with enhanced cognition in older women (Komulainen et al., 2008) and patients with coronary artery disease (Swardfager et al., 2011).

Based on the above evidence, moderate intensity aerobic exercise has been shown to have well established benefits for cognitive and cerebral heath, but what is the evidence for HI exercise? While there is not a large body of literature yet, there appears to be promising results for HI exercise and brain health.

In mice models, chronic HI aerobic exercise has been linked to increased VEGF-A and cerebral angiogenesis (Morland et al., 2017). This increase in VEGF-A was achieved after the mice underwent 7 weeks of HIIT, for 5 days a week which resulted in increased VEGF-A protein and capillary density, particularly in the dentate gyrus and other areas of the hippocampus. In a separate study using rats, it was found that after 8 weeks of training, the HI exercise group showed higher levels of cortical VEGF-A and striatal VEGF-R2 (Rezaei et al., 2018). Studies using humans have shown the same findings. In one study, participants underwent three different exercise protocols, but for the purpose of this paper we will focus on the two HI protocols: a HIIT (4 x 4 mins at 90-95% peak power output (PPO)) and an all-out protocol (4 x 30 sec of all-out exercise; Wahl et al., 2014). Compared to pre-exercise, post-exercise blood samples showed

significantly increased VEGF as well as increased levels of hepatocyte growth factor (HGF), a strong inducer of angiogenesis (Sengupta et al., 2003).

In terms of HI exercise and cognitive performance however, the evidence is less homogeneous. In one study, participants performed two exercise protocols on separate days: a MICE protocol at 60% peak VO2 for 30 min, and a HIIT protocol which included 4 min bouts at 90% peak VO2 (Tsukamoto et al., 2016). A color-word Stroop task was administered pre exercise and at 0, 10, 20, and 30 mins post exercise for both protocols. While both MICE and HIIT improved Stroop performance, the HIIT showed prolonged improvements compared to the MICE.

In another study, participants performed a running protocol at either low-intensity (LI; 40% VO2max), moderate intensity (MI; 60% VO2max), or HI (85% VO2 max; Wohlwend, Olsen, Haberg, & Palmer, 2017). MI and LI were continuous whereas HI consisted of four 4 min bouts at 85% VO2max and three 3 min bouts at 40% VO2max. Conner's continuous performance test (CCPT), a measure of sustained and transient cognitive control was administered after exercise. EF performance is represented by the participant's reaction time and accuracy on the CCPT. It was found that, after exercise, mean hit reaction time (i.e., the reaction time (RT) for correctly answered trials) decreased linearly with increased exercise intensity, indicating that HI exercise provided the greatest benefits. Additionally, compared to resting controls, HI protocols have been shown to enhance performance on the WCST (Hwang et al., 2016; Slusher, Patterson, Schwartz, & Acevedo, 2018), the trail making test (TMT; Hwang et al., 2016; Kujach et al., 2020), and Stroop (Alves et al., 2014; Kujach et al., 2020).

However, these results are not consistent in the literature. A study performed by Griffin and co-authors (2011) showed that, after a short period of HI cycling, participants exhibited improved performance on the face-name matching task, a measure of hippocampal function, but not the Stroop task. Another study revealed no difference in Stroop or TMT performance between a high-intensity aerobic exercise group (85-90% maxHR) and a self-myofascial release training control group (Obsterse, Bloch, Hübner, & Zimmer, 2016). A recent meta-analysis by Moreau and Chou (2019) further supports these findings by revealing that, after analyzing 28 studies, the effect of HI exercise on executive functions was only significant when compared to resting controls and not when compared to moderate exercise. Moreover, certain studies have shown MICE to enhance performance on tasks of executive function more than HI exercise (Brown & Bray, 2018; Ligeza et al., 2018).

The reason for this conflict in the literature might be due to the different mechanism in which MICE and HI exercise work in the brain. In one study, participants performed the Flanker task after either a bout of continuous aerobic exercise (60-70% HRmax) or a HIIT (90% HRmax interval) protocol (Kao, Westfall, Soneson, Gurd, & Hillman, 2017). Neurophysiological and behavioural measures were taken during the task, and it was found that HIIT resulted in improved performance on the task as well as shorter P3 latency. The P3 component of an event-related potential is associated with inhibitory control. In a similar study, participants performed the Go/No-Go and Flanker task while undergoing an fMRI scan after a bout of MICE (50-70% HRmax; 30 min continuous) and a HIIT session (> 70% HRmax during entire routine; Mehren et al., 2019). The MICE group showed improved behavioural performance on the Go/no-go

task as well as increased activation in areas related to executive function and attention. HI exercise resulted in decreased activation in those areas with no change in performance.

1.3 Objective

As discussed above, the effects of HI aerobic exercise on EFs are not clear. This could be due to various reasons, such as the intensity of the exercise protocol and when the cognitive tests were administered post-intervention. Alternatively, as evidence might suggest, these conflicts could be due to the underlying neuromechanical changes elicited by HI aerobic exercise that differ from those elicited by MICE. While exploration of the mechanistic component of this effect is beyond the scope of this review, exploring the characteristics of HI aerobic exercise and their impact on EFs is not.

To date, a comprehensive review of the literature characterizing the effects of a single bout of HI aerobic exercise on executive functions has yet to be conducted. A review such as this would allow for a better understanding of which EF domains are most, or least, sensitive to HI aerobic exercise. Thus, the primary goal of this review is to *explore the literature on the effects of an acute bout of HI aerobic exercise on executive functioning*, and to *specify which EF domains benefit from HI aerobic exercise*.

To address this goal, a scoping review was performed on all available literature that measured performance on tests of EF after a bout of HI aerobic exercise. We only included studies that recorded behavioural measures of cognitive performance (e.g., reaction time, % accuracy, etc.) as well as studies that used a quantitative measure of cardiovascular function (e.g., HRR, HR, PPO, maximal oxygen consumption, etc.). These criteria allow our review to specifically focus on various domains of EF, and to ensure that the studies themselves are using a defined high-intensity protocol. We expect the

results to show that certain EF domains benefit more from a short bout of HI exercise, while others may be negatively impacted. This scoping review will reveal to researchers which topics and areas are well covered in the literature and which areas need further investigation.

Scoping reviews are a tool used to synthesize information from a body of research with the intent to make broad observations on emerging evidence and to examine the typical protocols and data collection methods that are frequent (or infrequent) in the literature (Munn et al., 2018). Like systematic reviews, scoping reviews can also be used to identify knowledge gaps in the literature, though scoping reviews are typically used before conducting systematic reviews and therefore can be useful to identify these gaps early on. For these reasons, a scoping review was selected for the present work. The results from studies examining HI aerobic exercise and cognitive performance are inconsistent, particularly in the domain of EF. As such, the present work has the potential to identify a knowledge gap that researchers are unaware of that is causing this variation in data, or other factors may be revealed through comparing the different methodologies used within the field.

Chapter 2: Methodology

2.1 Search strategy

A scoping review was performed on literature involving the topics of HI aerobic exercise and executive functioning in order to investigate their interaction. Key words, subject headings, and all related terms, associated with those two concepts were identified through preliminary readings of relevant literature. The comprehensive search was performed in the following electronic databases: CINAHL (Appendix A), EMBASE (Appendix B), PsycINFO (Appendix C), SportsDiscus (Appendix D), and Medline at Ovid (Appendix E). The full search strategy developed for each of these databases can be found in the appendices listed above. There was no limitation on date of publication; the search ranged from inception to present.

The search strategy was developed a priori through collaboration with an information services librarian at Dalhousie University and followed the Preferred Reporting Items for Systematic Reviews and Metanalyses (PRISMA-P-ScR) guidelines for scoping reviews (Tricco et al., 2018). The search strategy was peer-reviewed by a second librarian using the Peer Review of Electronic Search Strategies (PRESS).

Databases were searched from inception to July 29, 2020. The search yielded 941 results, but after duplicates were removed, 610 papers remained for phase one screening. These papers were uploaded into Covidence where duplicates were automatically identified and removed. The remaining papers were screened via a three-phase screening process (described below) by two independent peer reviewers.

2.1.1 Screening Strategy and Inclusion/ Exclusion Criteria

Broadly, Phase 1 inclusion/exclusion criteria aimed to limit the number of studies included by identifying those broadly related to exercise and cognition in human participants. In Phase 2, the full text for papers remaining after Phase 1 were retrieved and screened by the same two independent reviewers using specific inclusion/exclusion criteria to address the objective of the scoping review. Finally, a third phase was included to ensure alignment with the scoping review approach. In cases of disagreement between the two independent reviewers in any phase of the screening, a third reviewer resolved conflicts. Detailed descriptions of the criteria are shown below in Tables 1 & 2.

Phase 1

The selection process for inclusion of studies was divided into three phases. Briefly, inclusion criteria for Phase 1 required studies to have human adult participants and include an aerobic exercise intervention that occurred in a single-bout that was described as “high intensity” or “vigorous”. Included studies also required a measure of cognitive function or ability, though at this stage we did not discriminate for specific cognitive domains – a study with any kind of cognitive testing/assessment was included. A detailed summary of phase 1 inclusion/exclusion criteria can be found in Table 1. The broader criteria for phase 1 was intended to narrow the scope of the papers to be screened in Phase 2, which is discussed below.

Table 1. Phase 1 inclusion/exclusion criteria

Inclusion Criteria	Exclusion Criteria
• Adult (≥18 years) human participants	• Animal models
• Includes a single-bout aerobic exercise paradigm described as "vigorous" or "high intensity"	• Foreign language articles
• A behavioral measure of cognitive performance	• Meta-analyses or reviews

Phase 2

Phase 2 further narrowed the scope of the papers in order to appropriately address the goal of the scoping review. Stricter criteria were placed on methodology, particularly with the AE protocols and the cognitive tests/assessments, to ensure that the exercise intervention was truly HI. Included studies were required to have a reliable physiological measure of cardiovascular function (e.g., % of HRmax, HRR, PPO). Predicted maximal heart rate was also considered as an acceptable measure to avoid excluding articles with older adult populations who, for safety reasons, may not have undergone a maximal exercise test. Studies that implemented a maximal exercise test as the exercise intervention were included when the intensity met the ACSM's guidelines for HI exercise.

Included studies had participants perform the exercise paradigm on either a cycle ergometer or a treadmill; implemented cognitive tests that targeted the specific domains of EFs; and administered these tests in either a pre/post protocol or as a control group/exercise group. Studies were excluded if the cognitive tests were administered at the same time as the exercise intervention, or if they implemented any chronic exercise or

cognitive training. Finally, studies were excluded if the participants were part of a clinical population (diabetic, diagnosed with MDD, PTSD, etc.) or specific health category (obese, overweight). A detailed list of Phase 2 inclusion/exclusion criteria is shown below in Table 2.

Table 2: Inclusion and Exclusion Criteria for Phase 2

Inclusion	Exclusion
• One or more behavioral measure(s) that assess executive function that can include working memory, attention, cognitive inhibition, response inhibition\suppression, cognitive flexibility • Healthy Adult participants (18 years or older) • A single acute bout of aerobic exercise that includes a high-intensity component and is performed via cycling or on a treadmill. Graded Maximal Exercise Test performed via cycling or treadmill is acceptable. • There is a quantitative measure of exercise intensity (VO2max > 70%; HRR > 70%; PPO > 70%; rated perceived exertions (RPE; 6 – 20) ≥ 15). • The accompanying PDF contains a full scientific article with methods/procedure and results section. • Comparisons of cognitive performance performed in either a pre/post intervention format or using an exercise/resting control group design.	• The aerobic exercise is combined with resistance training or cognitive training • The aerobic exercise is combined with some other experimental manipulation (e.g. sleep deprivation, caloric restriction, sham, placebo, drugs, hypoxia, etc.) • The study implements an aerobic exercise training regime • The authors do not report a quantitative measure of exercise intensity. • Adolescents & children. • Clinical population with physical (e.g. diabetes, cardiovascular disease, asthma, overweight, obese, etc.) or mental (PTSD, ADHD, anxiety, depression, addiction**,** mild cognitive impairment, autism, dyslexia, etc.) conditions • An exercise intervention other than cycling or treadmill running • Cognitive test is administered during aerobic exercise

Phase 3

A third phase was included in order to address the issue of availability of data to extract and include in the review, as well as to narrow the scope of the review to deal specifically with studies related to the stated objective. Studies were excluded if insufficient data were available to calculate an effect size. This encompassed studies in which: the raw data means and standard deviations were not made available; the raw data were only presented in graph form; or if demographic data related to the population studies were not included (e.g., age, sample size, health status).

2.1.2 Data Extraction

Data were extracted by a single reviewer using an extraction sheet created in Excel *a priori*. To characterize each study's population, data pertaining to age, health status, and sex were extracted as well as sample size for each group and any specific descriptors if applicable (e.g., previously inactive). Any health and cognitive screening was noted and, if applicable, the specific screening tool was extracted. The type of comparison being measured (pre/post or aerobic exercise group\rest group) and, if the latter, whether the comparisons were within- or between-subjects was extracted. If a maximal exercise test was performed the protocol details were extracted; alternatively, if no maximal exercise test was administered then the alternative method was also recorded (e.g., age predicted HRmax). For the exercise intervention protocol, the method of measurement (i.e., PPO, HRmax, VO2, etc.), target intensity, and mode (Ergometer or treadmill) was extracted. It was also noted if the protocol was continuous or composed of

intervals. If an interval protocol was used, the intensities and duration of the different intervals were extracted. For all intervention types, the total number of minutes spent in HI exercise was recorded. For cognitive tasks, the task(s) used were listed as well as the times they were administered pre/post relative to the exercise intervention. Finally, information relating to any mental/cognitive health screening used in the studies was extracted.

2.1.3 Data analyses

All information for the population and study methodology was tabulated. Studies that used the same cognitive tasks were tabulated together. Studies that administered the cognitive tasks at different time points were tabulated separately.

To compare across studies, we calculated Hedge's g effect size. The means and standard deviations were obtained from the studies for which data were extracted. As indicated above, if a study did not make the required data available in the text or accompanying tables it was not included. The mean, SD, and N for each group was placed into an Excel spreadsheet and Hedge's g was calculated using the formula found at the URL http://georgebeckham.com/2016/cohens-d-and-hedges-g-excel-calculator/. Depending on the study design, pre-exercise measurements were compared with post-exercise measurements OR resting controls measurements were compared with exercise group measurements.

Chapter 3: Results

3.1 Description of Data

In Phase 1, two independent reviewers screened the title and abstract of 610 studies based on the screening criteria outlined above. All conflicts were resolved by a third reviewer. After the first phase, 508 studies were excluded, leaving 102 studies for Phase 2 screening. In Phase 2, the full-text of these 102 studies were screened again permitting an in-depth review of the methodology and outcomes to ensure they met inclusion criteria for the review. At the end of the first two rounds of screening, 31 studies remained. These 31 studies were screened once more before the data were extracted to confirm eligibility. Following this final screen, one duplicate paper was identified and removed; three other papers were removed as they did not meet the inclusion criteria described in Figure 1 (i.e., they had erroneously been included). Two of these studies used anaerobic exercise while the third study implemented the cognitive task during the exercise intervention.

An additional seven studies were removed from analysis as they did not provide the required data to permit comparison across studies; specifically, mean values and a measure of variance (e.g., standard error of the mean, standard error, or standard deviation) were not reported in these studies. The final number of studies from which data was extracted was 16. The PRISMA diagram for the screening process is shown below.

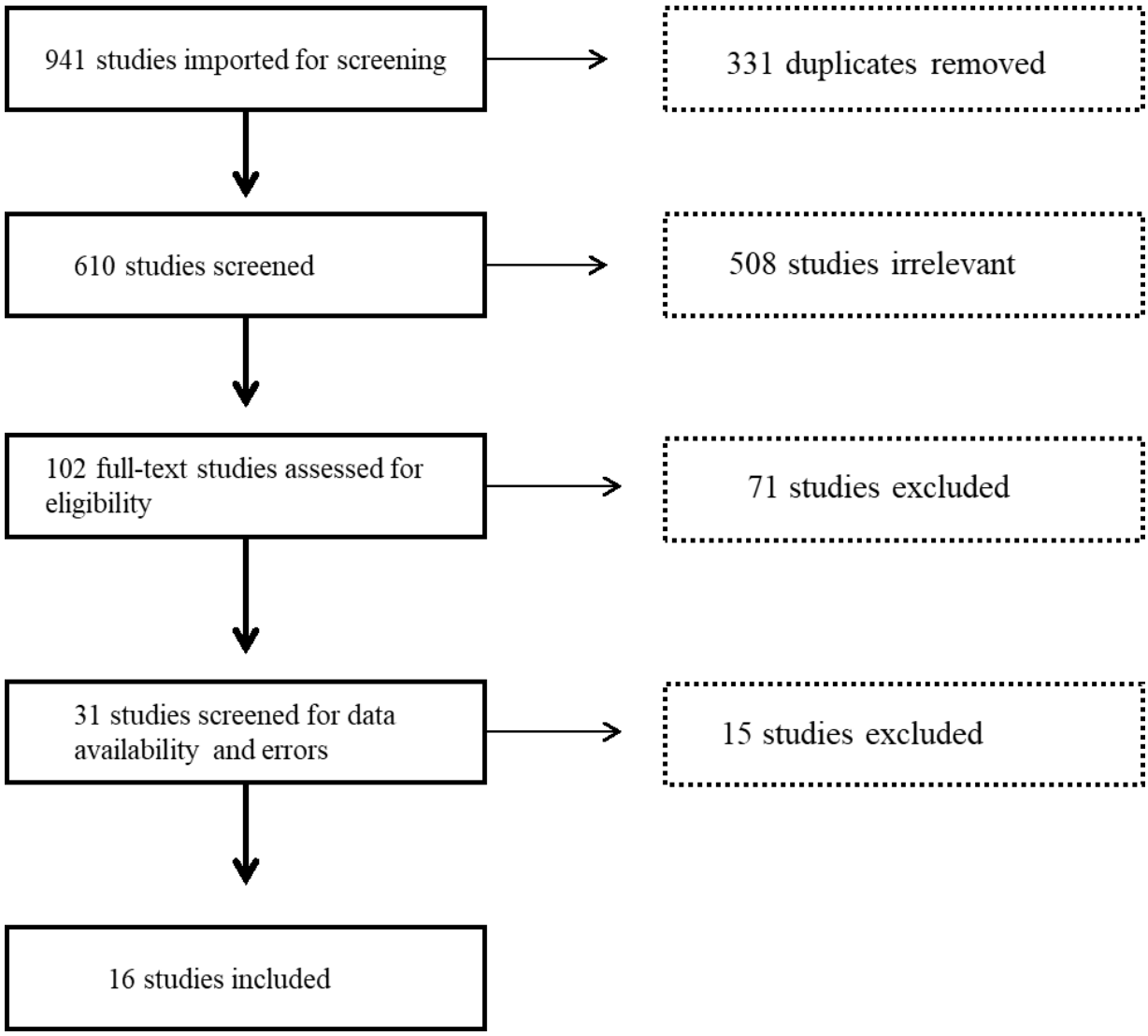

Figure 1. PRISMA flow chart of all phases of screening.

3.1.1 Participants

In total, 451 participants were tested across the studies; 60 of these participants were part of control groups but were included in the total as they were used in the calculations presented in the results. All but one paper reported the mean age of their participants; though the single paper that did not provide the mean age did report the age range of their participants to be within 19 – 27 years (N = 12). For the remaining 439

participants, we pooled together the mean age from across the studies, resulting in a value of 28.7 ± 15.0 years. Three studies included "older adult" groups specifically, which accounted for 44 of the total participant pool (M = 65.2 ± 7.2 years). After omitting these older adult participants, the remaining 395 participants had a pooled mean age of 23.3 ± 3.5 years. Twelve of the sixteen studies reported participant sex, resulting in 131 participants without sex-specific data. Of the 320 remaining participants, 206 were male and 114 were female.

3.1.2 Study design

Six of the sixteen extracted studies used a mental/cognitive screening tool. Study #1 used the Montreal Cognitive Assessment (MoCA) and the Beck Depression Inventory version 2 (BDI – II). Study #4 used the Brazilian Portuguese version of the BDI and the Brazilian version of the Mini-Mental State Examination (MMSE). Study #9 used the Kaufman Brief Intelligence Test (KBIT). Study #10 administered an intelligence quotient (IQ) test. Study #11 administered the German versions of the Structured Clinical Interview for DSM-IV (SCID-I), the SCID-II screening questionnaire for personality disorders, and the BDI-II. Finally, in Study #13 intelligence was captured using the Multiple Choice Vocabulary Test Version B (MWT-B).

Six of the sixteen studies used the physical activity readiness questionnaire (PAR-Q) to screen participants, while seven of the studies used their own screening methods. These alternative methods included medical examinations/doctor authorizations in the case of two studies, while other studies screened with specific inclusion/exclusion criteria. Thirteen studies used a graded maximal exercise test (GMXT) prior to the intervention. Out of the three studies that did not use a GMXT prior to the intervention,

one (#3) study used the GMXT as the intervention itself while the remaining two (#1 and 10) used an age predicted HRmax calculation in its place. For mode, thirteen studies used a cycle ergometer with the remaining three using a treadmill.

When looking at the quantitative measures of exercise intensity (e.g., HRmax, PPO etc., the methods varied with no single measure being used more than the others (Figure 2A). The various cognitive tasks used across the studies is depicted in Figure 2B. It should be noted that one cognitive task is listed as the NIH cognitive battery. This is a cognitive battery that consists of four cognitive tasks including: Flanker, working memory, fluid cognition, and card sort. Like other versions of the Flanker, the one used in the NIH cognitive battery assessed inhibition. The fluid cognition task is described as assessing overall executive function, while the card sort assesses cognitive flexibility.

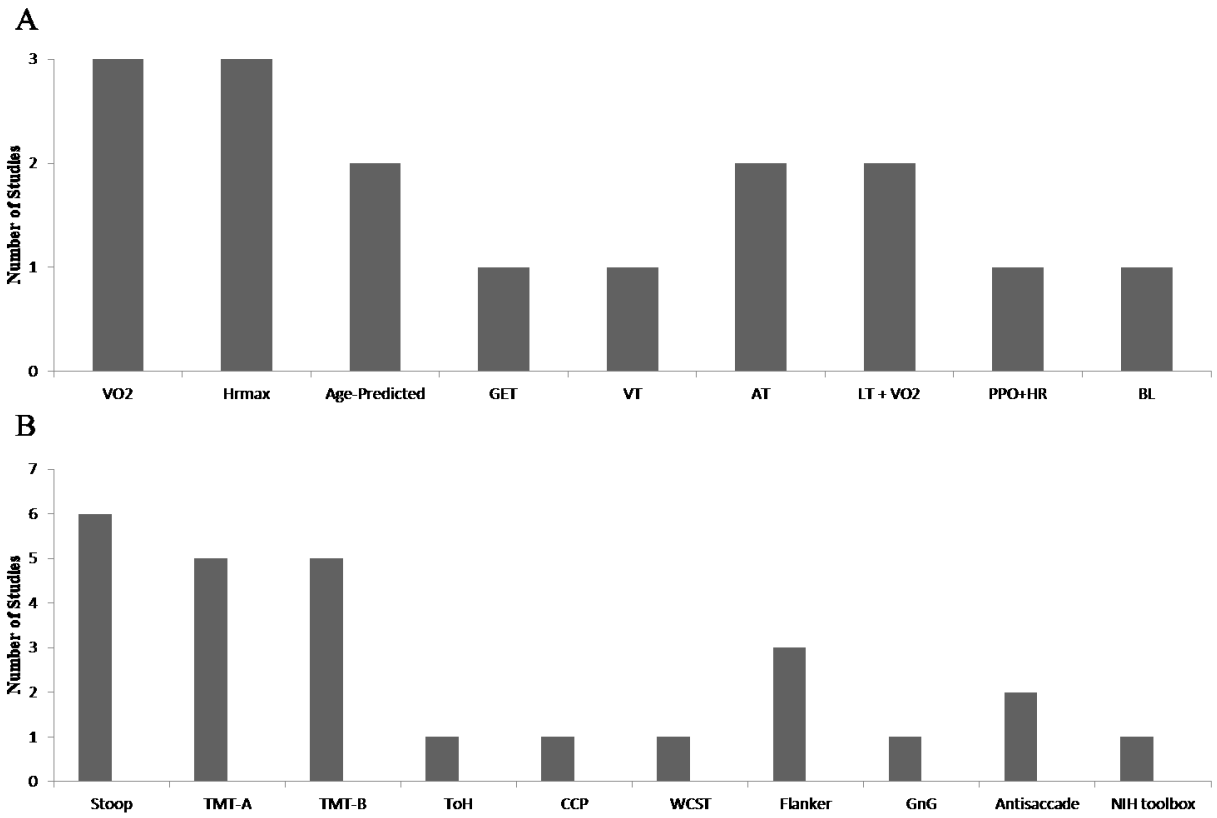

Figure 2. Methodologies used across studies. A) Measures of exercise intensity and prescription. Maximal oxygen consumption (VO_2); Peak power output (PPO); maximum heart rate (HRmax); Age predictive heart rate (Age-Predicted); gas exchange threshold (GET); ventilatory threshold (VT); anaerobic threshold (AT); blood lactate (BL). B) Distribution of cognitive tasks across studies.

A thorough review of the design of each study revealed that out of the 16 studies, seven tested multiple experimental groups. For example, Aguirre-Loaiza et al (2019) performed the same intervention on both a sample of active and inactive participants. Coco et al (2020) used two different groups to study the effects of exercise on older and younger participants separately, and several studies that did not use a pre/post study

design had two different groups for exercise vs control. Therefore, while 16 studies were included in the review, a total of 23 groups of participants were studied. Of these 23 groups, 19 used a within-subject design while the remaining four (2 exercise and 2 control groups) used a between-subject design. Figure 3 illustrates the distribution of interventions across the 23 groups. Seven groups engaged in a HIIT intervention while twelve engaged in a HI continuous (HIC) intervention. Two groups (both from study #3) underwent an exhaustive exercise protocol. Finally, two of the 23 groups were control groups and therefore did not engage in any physical activity. In the remaining graphs and tables presented in this thesis, these control groups are not shown since they are not experimental groups and were used in exercise vs control comparison only.

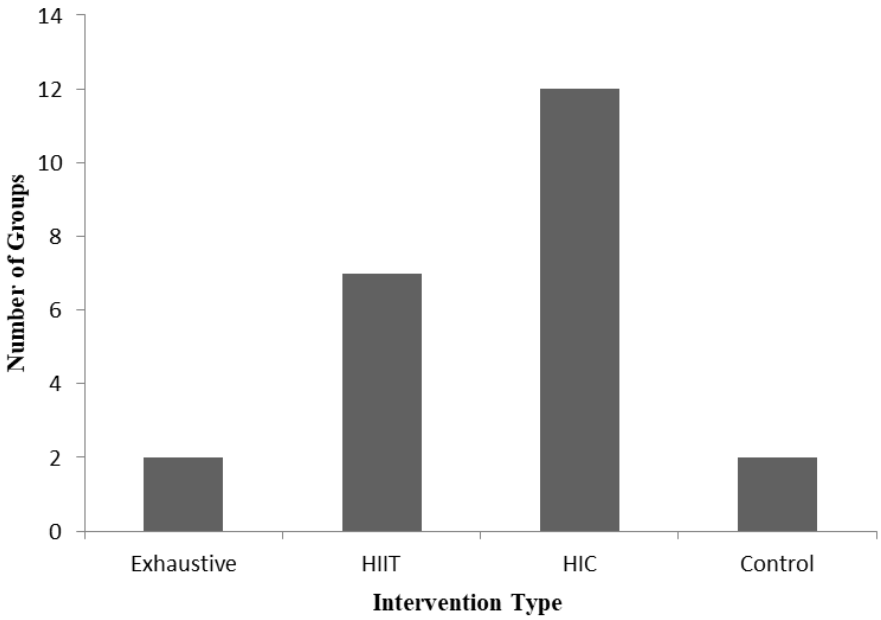

Figure 3. Distribution of intervention type for each individual group extracted from the studies.

3.2 Analysing the data

To compare across studies, we calculated Hedge's g effect size. The means and standard deviations were obtained from the studies for which data were extracted. As indicated above, if a study did not make the required data available in the text or accompanying tables it was not included. Of all the effect sizes calculated, 45.9% reflected the effect of the exercise intervention on the inhibition domain; 16.5% on the attention domain; 20% on the working memory domain; and 17.6% on the cognitive flexibility domain. Interpretation of Hedge's g followed the standard interpretation for Cohen's d in which an effect below 0.2 is considered "null". Between 0.2 and 0.49 was a small effect, between 0.5 and 0.79 was a moderate/medium effect, and all values above |0.8| were a large effect. The magnitude of the effect is represented by the number and the direction of the effect is described in the text. To facilitate the discussion of the results, Table 3 presents the individual studies and sub-groups within a study, with each assigned a numerical code for ease of identification.

Table 3: Studies ordered by first authors name with accompanying number/letter code.

Study No.	Author(s)	Year	Intervention								
			GXT?	Modality	AE type	Intensity	Unit	Duration Mins	Mean Age	Comparison	N
1A	Aguirre-Loaiza	2019	N	Ergonometer	HIIT	75-85%	HRmax	35	20.7	W	25
1B	Aguirre-Loaiza	2019	N	Ergonometer	HIIT	75-85%	HRmax	17	21.6	W	10
2A	Brown	2018	Y	Ergonometer	HIIT	70%	Watts	10	19.9	W	22
2B	Brown	2018	Y	Ergonometer	HIC	80-90%	HRmax	20	19.6	W	22
3A	Coco	2020	N	Ergonometer	Exhaustion	Incremental	Watts	Var	24.7	W	15
3B	Coco	2020	N	Ergonometer	Exhaustion	Incremental	Watts	Var	58.9	W	15
4	Córdova	2009	Y	Ergonometer	HIC	90%	AT	20	63.8	W	12
5	Del Giorno	2010	Y	Ergonometer	HIC	100%	VT	25	20.2	W	30
6	Du Rietz	2019	Y	Ergonometer	HIC	20% difference between GET and VO2peak	GET, VO2	10	21.5	W	29
7A	Heath	2018	Y	Ergonometer	HIC	15% of the difference between LT and VO2 peak	LT, VO2	10	19-27	W	12
7B	Heath	2018	Y	Ergonometer	HIC	50% of the difference between LT and VO2 peak	LT, VO2	10	19-27	W	12
8	Hwang	2016	Y	Treadmill	HIC	85-90%	VO2	10	22.8	W	29
9	Ligeza	2018	Y	Ergonometer	HIIT	25% of difference between Pmax and Pvt2	Pmax, VT	12	24.9	W	18
10	Loprinzi	2015	N	Treadmill	HIC	71-85%	AP-HR	30	22.3	W	22
11	Mehren	2019	Y	Ergonometer	HIIT	>70%	Hrmax	21	28.6	W	31
12	Moriarty	2019	Y	Ergonometer	HIIT	85-90%	VO2	10	35	W	8
13	Oberste	2016	Y	Ergonometer	HIC	85-90%	HRmax	35	23	B	30
14A	Petrella	2019	Y	Treadmill	HIC	15% of the difference between LT and VO2peak	LT, VO2	10	73	W	17
14B	Petrella	2019	Y	Treadmill	HIC	50% of the difference between LT and VO2peak	LT, VO2	10	73	W	17
15	Tsukamoto	2016	Y	Ergonometer	HIIT	90%	VO2	16	22.9	W	12
16	Zimmer	2016	Y	Ergonometer	HIC	85-90%	HRmax	30	23.9	B	30

Table 3 legend: Acronyms in order present in table: Var (variable), AT (Anaerobic threshold), VT (ventilatory threshold), GET (gas exchange threshold), LT (lactate threshold), Pmax (power max), Pvt2 (power at ventilatory threshold 2), and AP-HR (age predicted heart rate max).

3.2.1 Inhibition

To investigate the effect of the exercise intervention on this cognitive domain, outcome measures produced by the Stroop, Flanker, Go/No-Go, Tower of Hanoi (ToH), and antisaccade tasks were used. For the Go/No-Go, the sensitivity index (*d'*) and correct inhibition rate score were collected. Due to the numerous outcome measures used by each study, in order to make comparisons, only one outcome measure per cognitive task was used to represent the overall performance. These outcome measures were decided separately for each study as not all studies, despite using the same cognitive tests, measured the same outcomes. As a general rule, if the studies used an interference score then that was the outcome measured used to represent the cognitive task. Alternatively, if no interference score was available then the main outcome measure, as identified by each paper, was used in its place. A summary of the results for inhibition is shown below in Table 4. A more detailed breakdown of each effect size per outcome can be seen in Appendix B, Table 8.

Table 4. Summary of effects of exercise on the cognitive domain inhibition. Note a negative (-) effect size can reflect a positive effect of exercise on inhibition based on the outcome measure used in the given study.

Test	Study #	Positive Effect of Exercise on Cognitive Domain?		Effect Size (*g*)
		Yes	No	
Stroop	1A	X		0.76
	1B	X		0.97
	2A	X		0.34
	2B	X		0.44
	3A		X	1.47
	3B		X	3.83
	8	X		0.48
	13	X		0.49
	15		X	0.75
	16	X		0.26
Flanker	6		X	0.19
	9		X	0.16
	11		X	0.10
	12		X	0.19
Go-No-Go	11		X	0.09
Antisaccade	7A	X		0.22
	7B		X	0.17
	14A	X		NR*
	14B	X		NR*
ToH	4	X		0.59

* *Data weren't available to calculate effect size*

3.2.1.1 Stroop.

Six studies used variations of the Stroop task (Studies #1, 2, 3, 8, 13, and 15). Three studies (#2, 3, and 15) measured performance at multiple time points after exercise, which is why some groups are repeated throughout the results. Four studies (#1, 2, 8, 13) showed an increase in cognitive performance based on the effect sizes which included small (2A, 2B, 8, 13), medium (1A, 2A), and large (1B) effects, though the majority were small.

Study #1 had two experimental groups in which physically active (1A) and physically inactive (1B) participants engaged in the same HIIT protocol at 75-85%

HRmax, although 1B exercised for only 17 mins at that intensity compared to 35 mins for 1A. Despite the shorter exercise protocol, study 1B had a large positive effect size (0.97) while 1A had a medium positive effect size (0.76). For this study, the number of "right choices" during the Stroop task was used to measure performance.

In study 2A, participants performed a HIIT protocol for 20 mins in total, alternating between 1 min bouts at 70% peak aerobic power (W) and 1 min bouts at 12.5% W. In 2B, the protocol consisted of 20 mins of continuous exercise at 80-90% HRmax. Measures were taken pre-exercise as well as 0 and 10 mins post for both groups. When tested at 0 mins, both groups only showed a small positive change in performance (2A = 0.34; 2B = 0.44). After 10 mins, 2A – the HIIT group – showed a medium-sized positive effect of exercise on inhibition (g = 0.63) while the effect observed in study 2B remained small (g = 0.40).

Study #8 used a 10 min continuous exercise protocol performed on a treadmill at 85-90% VO2max, with a small positive effect of the exercise on inhibition found (g = 0.48). Finally, in study #13, participants underwent a 35 min continuous protocol on an ergometer at 85-90% HRmax. The results showed a small positive effect (g = 0.49) of exercise on inhibition.

The two subsequent studies (#3 and 15) showed decreased performance of inhibitory processes following the exercise intervention. In study #3, two groups were used to investigate the effects of exercise on youth (3A) and older adults (3B) using an incremental ergometer protocol. Participants in both groups exercised until they reached volitional exhaustion. As such, the duration of exercise varied for each individual.

Cognitive measures were taken at 0 and 15 mins post exercise. Both studies 3A and B showed a large negative effect of exercise on cognition at the 0 min-post exercise (g = 1.47 and 3.83 respectively); 15 mins later study 3A had a small negative effect (g = 0.11) while study 3B still had a large negative effect (g = 3.35).

In study #15, participants underwent a HIIT protocol for 33 mins (four 4-min bouts at 90% peak VO2 with 3-min intervals at 60% peak VO2) on an ergometer. Measures were taken at 0, 10, 20, and 30 mins post exercise. The 0 (g = 0.75), 20 (g = 0.67), and 30 (g = 0.51) min time points each exhibited a negative medium-sized effect of exercise on cognitive performance (inhibition in this instance). At the post-10 min mark, the negative effect was large (g = 0.80).

Finally, in Study #16, participants performed a continuous ergometer protocol at 85-90% HRmax for 30 mins. The effect size calculated was 0.26, indicating a small but positive effect of exercise on inhibition.

3.2.1.2 Flanker.

The Flanker task was used in four of the studies (#6, 9, 11, and 12) with various measures of interference and reaction times. As the Flanker is often used as a test of both inhibition and attention, it was placed in both cognitive domains.

Of the four studies, three used ergometers and one (#9) used a treadmill. Two of the four studies (#6 and 9) implemented a continuous exercise protocol but used a different exercise intensity and method of measurement. For study #6, the intensity was set at a 20% difference between the GET and VO2 peak, with a duration of 10 mins. The negative effect size for the Flanker inhibition score was just below 0.2 for this study (g =

0.19). Study #9 used an intensity set at a 25% difference between Pmax (maximum power) and Pvt2 (power at VT2) for 12 mins. This study also had an effect size below 0.2, though it was positive (g = 0.16). The remaining two studies (#11 & 12) both used a HIIT exercise protocol. In study #11, the authors described the intervention as "short bursts of HI cycling interspersed with varied recovery times" which lasted for 21 mins in total. While the exact intensities of the high-intensity bouts and recovery times were not described, the authors state that during the whole routine the intensity was above 70% of the individual's HRmax. The effect size calculated for this study was negative and below 0.2 (g = 0.10). In study #12, participants exercised for 30 mins with 1 min bouts of high-intensity exercise (85-95% of the workload achieved during the VO2max test) interspersed with 2 mins of rest at 40% of the workload achieved during the VO2max test. The effect size determined for this study was negative and just below 0.2 (g = 0.19).

3.2.1.3 Go/No-Go.

The Go/No-Go task is a classic inhibition test that was used in only one of the studies (study #11), which was described in the section above. The authors used a measure called the *sensitivity index d'* as the main outcome measure for the Go/No-Go. No effect of exercise was found for this particular study (g = 0.09).

3.2.1.4 Antisaccade.

Two studies used outcomes generated from antisaccades, which measures inhibition by recording the participant's ability to inhibit automatic saccadic movements towards a stimulus. In study #7, the authors investigated the effect of two different exercise intensities on inhibition; study #7A had participants exercise continuously at a 15% difference between the lactate threshold (LT) and VO2 peak for 10 mins on an

ergometer while study #7B had participants exercise at a 50% difference between LT and VO2 peak for 10 mins on an ergometer. Study #7A showed a small positive effect size for exercise on inhibition (g = 0.22), with the negative value indicating a decrease in reaction time, and therefore, an improvement in performance. Study #7B did not have an effect size above 0.2 (g = 0.17). The other study to use antisaccade data was #14 in which two different exercise intensities were used. In #14A, participants exercised at a 15% difference between the lactate threshold and VO2peak for 10 mins, while#14B used a 50% difference. Both exercise protocols were continuous on a treadmill for 10 mins. Due to incomplete data, the effect size for this study could not be calculated. Nonetheless, it was reported that the exercise intervention decreased antisaccade reaction times significantly ($p<0.01$) in their study for both groups.

3.2.1.5 Tower of Hanoi.

The final task used for investigation of the effect of exercise on the cognitive domain of inhibition is the ToH, which was used in study #4. The ToH recruits both working memory and inhibitory processes, therefore it is included in the results in both categories (see '*Working Memory*' below). Participants in study #4 exercised on an ergometer at 90% of their anaerobic threshold (AT) continuously for 20 mins. The main outcome for the ToH was *total number of moves*; analysis of the results produced a medium positive effect size (g= 0.59) indicating a moderate effect of exercise on the cognitive domain of inhibition.

3.2.2 Working Memory

Two of the included studies investigated the effect of exercise on working memory. One study (#4) did so using ToH (described above) while the second (#12) used

the *NIH Toolbox® fluid cognition battery assessment* to study working memory, as well as attention and cognitive flexibility (Moriarty et al., 2019). The NIH Toolbox® is a set of neuro-behavioural measures that can evaluate emotional, cognitive, sensory, and motor functions (Hodes, Insel, & Landis, 2013). For each domain tested, a single outcome measure was produced and will be discussed in detail below. A summary of the results for working memory is shown below in Table 5. A more detailed breakdown of each effect size per outcome can be seen in Appendix B, Table 9.

Table 5. Summary of effects of exercise on the cognitive domain working memory. Note a negative (-) effect size for the ToH reflects a positive effect of exercise on working memory based on the outcome measure used in the given study.

Test	Study #	Positive Effect of Exercise on Cognitive Domain?		Effect Size (*g*)
		Yes	No	
ToH	4	X		0.59
NIH Toolbox "Working memory"	12		X	0.09

3.2.2.1 Tower of Hanoi.

As with many cognitive tasks, it can be difficult to tease apart the multiple EFs recruited and their specific role in the outcome measure. As mentioned above, the ToH is also used to measure inhibition. Given the outcome *total number of moves* assesses working memory as well as inhibition, the medium positive effect size (stated in the above section; g = 0.59) found in study #4 indicates a moderate effect of exercise on working memory, meaning that participants were able to solve the task using fewer moves after exercise than before.

3.2.2.2 NIH Toolbox® – Working memory.

Study #12 was the only study to use the NIH Toolbox, and among the four tests used in the battery, one assessed working memory. As indicated, participants in study #12 engaged in HIIT that involved 1 min intervals at 85-95% peak power interspersed with 2 mins at 40% for 30 mins. The effect size for study #12 was found to be below 0.2 (g = 0.09), indicating no effect of the HIIT intervention on working memory.

3.2.3 Cognitive Flexibility

Outcome measures used in the assessment of cognitive flexibility were taken from the TMT-B, NIH Toolbox®, and the WCST. A summary of the results for inhibition is shown below in Table 6. A more detailed breakdown of each effect size per outcome can be seen in Appendix B, Table 10.

Table 6. Summary of effects of exercise on the cognitive domain cognitive flexibility. Note a negative (-) effect size can reflect a positive effect of exercise on cognitive flexibility based on the outcome measure used in the given study.

Test	Study #	Positive Effect of Exercise on Cognitive Domain?		Effect Size (*g*)
		Yes	No	
TMT-B	1A	X		0.71
	1B	X		0.28
	4	X		0.26
	8	X		0.80
	10	X		0.24
	13		X	0.08
WCST	5	X		0.55/0.22
NIH Toolbox "Card Sort"	12	X		0.48
NIH Toolbox "Fluid Cognition"	12	X		0.23

3.2.3.1 Trail Making Task B.

In the TMT-B task, performance is measured by timing how long it takes for the participant to complete the task. Five studies used the TMT-B (studies #1, 4, 8, 10, and 13). Several of these studies were described previously, but their details are repeated here for ease of reading. Study #1 had two groups; 1A included "active" individuals and 1B included "inactive" individuals. Both groups underwent a HIIT paradigm with the HI interval being 75-85% HRmax. In 1A, there was a large positive effect (g = 0.71) of exercise on cognitive flexibility, while a small but positive effect of exercise on cognitive flexibility was found for 1B (0.28).

Study #4 had participants exercise continuously on a cycle ergometer for 20 mins at 90% AT. The effect size calculated for this study showed a small positive effect of exercise (g = 0.26).

Study #8 and 10 used a treadmill as their mode of exercise. Study #8 used a continuous paradigm at 85-90% VO2max for 10 mins and found a large, positive effect of exercise (g = 0.80), while study #10, which also used a continuous paradigm in which the intensity ranged from 71-85% of the age-predicted HRmax for 30 mins, showed a small positive effect (g = 0.24).

The final study to be discussed in this section is study #13 which used a cycle ergometer to employ a 35 min continuous protocol at an intensity of 85-90% HRmax. This study showed no effect of exercise on cognition (g = 0.08).

In summary, two of the studies showed a large effect of exercise on cognitive flexibility (#1A and 8), three had a small effect (#1B, 4, and 10), and one study showed no effect (#13).

3.2.3.2 Wisconsin Card Sorting Task.

Only one of the included studies administered the WCST (study #5), which was given pre-exercise and then immediately after (post-0) and then again 20 mins (post-20) after the exercise. Using a cycle ergometer, participants exercised continuously at 100% VT for 25 mins. While several outcomes result from the WCST, *perseverative errors* are most reflective of behaviours and cognitive abilities that arise from prefrontal activity (Barcelo & Knight, 2002), and therefore was used in this review as the main outcome measure. When tested immediately after exercise, a positive medium sized effect of exercise on cognitive flexibility ($g = 0.55$) was found. When tested again 20 mins later, the effect was positive and small ($g = 0.22$). Both these values are listed in the table above, separated with a "/" symbol.

3.2.3.3 NIH Toolbox®

Of the four tasks included in the NIH Toolbox used in study #12, two targeted the domain of cognitive flexibility. The first cognitive test was "card sort", which assesses overall executive function. The exercise intervention employed in study #12 had a medium sized positive effect on the outcome of the card sort task ($g = 0.48$), suggesting a moderate effect of the exercise intervention. The other test called was termed "fluid cognition" which had a small positive effect size ($g = 0.23$).

3.2.4 Attention

For attention, outcomes were taken from the Flanker, the contingent continuous performance (CCP) task, and the TMT-A. A summary of the results for inhibition is shown below in Table 7. A more detailed breakdown of each effect size per outcome can be seen in Appendix B, Table 11.

Table 7. Summary of effects of exercise on the cognitive domain attention. Note a negative (-) effect size can reflect a positive effect of exercise on attention based on the outcome measure used in the given study.

Test	Study #	Positive Effect of Exercise on Cognitive Domain?		Effect Size (*g*)
		Yes	No	
TMT-A	1A	X		0.91
	1B	X		1.29
	4	X		0.43
	8	X		0.63
	10	X		0.28
	13		X	0.13
Flanker	6		X	0.19
	9		X	0.18
	11		X	0.10
	12		X	0.19
CCP	5		X	0.0

3.2.4.1 Flanker.

The Flanker task can be used to test inhibition as well as attention. Whereas interference scores for the Flanker are attributed to inhibitory processes, for attention we used the reaction times (incongruent) and number of errors (incongruent) to investigate the effect of exercise on attentional performance. For a more accurate measure of attention, both number of errors and reaction times should be considered, but for simplicity's sake, only number of errors were compared across the four studies which

used the Flanker (#6, 9, 11, and 12). As these studies have previously been described, only information pertinent to this section will be repeated for clarity.

In study #6, participants exercised for 10 mins at an intensity that was set at a 20% difference between the GET and VO2 peak. The effect size for Flanker *errors* score was found to be just below 0.2 for this study (g = 0.19), indicating no effect of the exercise on attention. Participants in study #9 exercised for 12 mins at an intensity set at a 25% difference between Pmax (power max) and Pvt2 (power at VT2). Similar to study #6, no effect of exercise was observed on attention for study #9 (g = 0.18), although it should be noted that this effect size was calculated for *response accuracy* as opposed to error score. Consistent with the findings of studies #6 and 9, study #11 also showed no effect of exercise on attention (g = 0.10) following 21 mins of a HIIT paradigm with varying duration high and low-intensity intervals above 70% HRmax. Following exercise for 30 mins with 1 min bouts of high-intensity exercise (at 85-95% of the workload achieved during the VO2max test) interspersed with 2 mins of rest at 40% intensity, study #12, which used the NIH Toolbox version of the Flanker task, also did not show an effect of exercise on attention (g = 0.19). In summary, none of the four studies that used the Flanker task to assess the cognitive domain of attention showed an effect of exercise.

3.2.4.2 Contingent Continuous Performance.

In study #5, the authors used the CCP to measure attention both immediately after, and 20 mins after exercise. Participants exercised continuously on a cycle ergometer for 25 mins at VT. The effect sizes for both the 0-min post exercise (g = 0) and 20-mins post exercise (g = 0.09) were below 0.2, indicating there was no effect of exercise on attention at either time point.

3.2.4.3 Trail Making Task A.

All studies that used the TMT-A (#1, 4, 8, 10, and 13) were described in the previous "Trail Making Test B" section. Study #1A (active group) showed a positive effect size of 0.91 while #1B (inactive group) showed a positive effect size of 1.29. Both groups therefore displayed a large effect of exercise on attention as measured by the TMT-A. While smaller in magnitude, studies #4 and 8 also showed an effect of exercise on attention. Study #4, which used a 20 min continuous exercise protocol at 90% AT, showed a small positive effect of exercise on attention ($g = 0.43$), while study #8, which used a continuous treadmill protocol at 85-90% VO2max for 10 mins, showed a positive medium sized effect ($g = 0.63$) of exercise on attention. Study #10, in which participants exercised on a treadmill continuously at 71-85% age-predicted HRmax for 30 mins, also showed a positive effect of exercise on attention, although the effect was small ($g = 0.28$). Unlike the other studies that used the TMT-A to assess attention, study #13 did not show an effect of exercise. In this study, participants continuously exercised at 85-90% HRmax for 35 mins, with results showing an effect size below 0.2 ($g = 0.13$).

In summary, of the six studies that assessed attention using the TMT-A, two showed a large effect, one showed a medium effect, two showed a small effect, and one showed no effect.

Chapter 4: Discussion

The purpose of this review was to *explore the literature on the effects of an acute bout of HI aerobic exercise on executive functioning*, and to *specify which executive function domains benefit from HI aerobic exercise*. Five databases were searched yielding 941 studies. After four rounds of screening, 16 studies were included, and data extracted and analysed. The overall findings suggest that HI aerobic exercise neither improved nor decreased performance on tasks that assessed the domains of inhibition, working memory, and attention. The domain of cognitive flexibility, however, showed a distinct improvement in performance following HI aerobic exercise whereby eight out of nine studies showed an effect. Nonetheless, the main takeaway of this review is that the results are too varied within the majority of EF domains to draw any conclusions or identify trends regarding the effect of HI aerobic exercise. The following discussion explores the major contributing factors thought to be the cause of the variability in the findings across studies.

4.1 Variability in Exercise Procedure

In a review by Chang, Labban, Gapin, & Etnier (2012), the authors highlighted four primary moderators of cognitive performance after a bout of acute exercise: exercise intensity, time of cognitive test administration and duration, general cognitive task type, and fitness of participants. In the current review, many of the moderators presented by Chang et al (2012) are relevant to the interpretation of the results. As exercise intensity is the main variable investigated in this review, it will be given the most attention. The variations in exercise intensity and duration across studies will be explored in their

relation to the variability of the results and how these factors might uniquely change underlying neural mechanisms that may impact on the domains of executive function explored. The second factor that must be considered and discussed are the differences in cognitive tasks, particularly when there are multiple versions of the same task (e.g., Computerized Stroop vs Pencil & Paper Stroop). This part of the discussion will also touch on the difficulties, and perhaps even the failure, of using cognitive tasks to measure a single aspect of a specific EF. The third relevant factor in need of exploring is the discrepancy in the time delay between the end of exercise and when the cognitive task was administered. Finally, recommendations for future literature will be proposed with the intention of creating standards in the research examining the effect of HI aerobic exercise on executive function that will allow for comparison across studies.

Across all studies, there did not appear to be any trend in terms of mode of exercise (e.g., ergometer vs treadmill). When considering the different exercise protocols (HIIT, HIC, and exhaustive) there does seem to be some difference in the effect of the exercise when data is group together based on this attribute. For instance, 17 of the data points were from studies that used a HIIT protocol, with 9 out of 17 of the data points showing an effect of exercise (~ 53%). Meanwhile, 20 data points were taken from studies that used a HIC protocol, with 14 of the 20 showing an effect of the exercise (70%). Finally, only one study used an exhaustive exercise protocol in both young and old adults, but there were no effects of exercise on cognition observed for either group. While the HIC protocol seems to have the most evidence supporting an effect of exercise, it would be inaccurate to claim that continuous exercise is more beneficial than HIIT as numerous confounding variables need to be taken into account. While the scope of this

review does not go into detail for all potential variables, it is worth exploring the differences and similarities between HIIT and HIC.

As mentioned in the introduction, both continuous and interval exercise increase BDNF and other neurotrophic factors. Summarizing the results of numerous studies in their review on HIIT and BDNF, Jiménez-Maldonado and co-authors (2018) suggested that, as compared to MICT, HIIT increased mitochondrial activity and reactive oxygen species (ROS), causes greater Ca^{2+}concentration in neurons, and elevates systemic blood lactate concentration. All these changes are part of larger pathways that eventually increase BDNF production in the brain. Indeed, one of the extracted studies used in the current review measured BDNF levels alongside executive performance. Hwang et al (2016; Study #8) found a significant relationship between BDNF levels and performance on the TMT-B after a bout of continuous exercise. The authors conclude that changes in BDNF concentrations could be partially responsible for the improvement in prefrontal-dependent cognitive performance following exercise. Furthermore, other studies have shown HIIT to be more effective in increasing systemic serum BDNF levels as compared to MICT. In a study performed by Saucedo Marquez, Vanaudenaerde, Troosters, & Wenderoth (2015), participants performed both an intensive continuous exercise protocol at 70% of maximal work rate and a HIIT protocol at 90% of maximal work rate for periods of 1 min alternating with 1 min of rest. Both protocols lasted 20 min and it was found that the HIIT protocol increased BDNF levels to a greater amount than the continuous protocol. Nonetheless, both protocols increased BDNF concentration and therefore it is reasonable to suggest that improvements in cognitive performance following either the HIC or HIIT protocol could be a result of increased BDNF, although

it is impossible to know if this correlation between neurotrophic factors and change in cognitive performance is consistent across all extracted studies. In a study partially inspired by the Hwang et al (2016) study, Slusher et al (2018) investigated how a HIIT protocol would impact performance on the WCST and neurotrophic factors. It was found that, following the HIIT protocol, performance on the WCST and serum BDNF concentrations both increased, but were independent of each other. As the authors suggest, there is a need to further examine the mechanisms underlying the effect of the HIIT on cognitive performance.

Other studies have also suggested that BDNF might work alongside stress hormones to enhance cognitive performance. In their study, Martínez-Díaz et al (2020) studied the effects of HIIT on neurocognitive and stress biomarkers in relation to working memory capacity in healthy young male adults. Briefly, participants completed 10 x 1-min bouts of cycling at their VO2 peak power output, interspersed with 1-min bouts of passive rest (feet resting on the pedals with no movement). BDNF, cortisol levels and working memory was assessed at three time points: pre intervention, post intervention, and 30-mins post intervention. The results showed a significant increase in circulating BDNF and cortisol concentration coinciding with the highest working memory performance, though there was no statistical association between the cognitive and neuroendocrine variables. The authors propose an explanation whereby HIIT increases arousal and neuronal activation in areas related to working memory.

While HIIT may be more effective relative to other exercise protocols at increasing BDNF concentration, the relationship between neurotrophic factors and cognitive performance is not straightforward. Indeed, the intensity and duration of the

exercise are important to consider when interpreting the results of the current review. There were large variations in intensity and duration across the studies included which, as will be discussed below, likely contributed to the variation in results. For example, in Study #7, two different exercise protocols were used. In group 7A participants exercised at a "heavy" intensity (15% of the difference between LT and VO2 peak) while those in 7B exercised at "very heavy" (50% of the difference between LT and VO2 peak). It was found that group 7A showed an effect of exercise on inhibition, while group 7B did not. This finding could suggest an intensity threshold at which, once crossed, exercise no longer improves cognition, at least in the domain of inhibition.

Indeed, previous research has suggested LI exercise produces the greatest increases in cell proliferation (Kim et al., 2003) and neurogenesis (Lou, Liu, Chang, & Chen, 2008). Heavy exercise, contrastingly, has been suggested to impede cognitive performance. One proposed pathway by which exercise can hinder or help cognition is through modulating catecholamine activity. Catecholamine levels are known to increase with the duration and intensity of exercise (for a review see: Zouhal, Jacob, Delamarche, & Gratas-Delamarche, 2008) and their elevated levels may be responsible for decreased cognitive performance. High concentrations of norepinephrine and dopamine leads to increased activation of prefrontal α^1-adrenoceptor which reduces neuronal firing, as well as increases stimulation of D^1-receptors and β-adrenoceptors which dampen neuronal activity (for review see: McMorris, 2016). Other meta-analyses support the detrimental effect of HI exercise on cognitive processes (Chang, Labban, Gapin, & Etnier, 2012; McMorris & Hale, 2015), making reference to the inverted-U theory of arousal as well as the reticular activation hypofrontal hypothesis as proposed by Dietrich (2003; Dietrich &

Audiffren, 2011). According to Dietrich's theory, heavy exercise, as compared to moderate exercise, requires greater activation of the premotor cortex and supplementary motor areas and this activation remains high in order to maintain the exercise intensity. This demand for energy comes at the expense of the PFC, and as a result, cognitive functions that rely on the PFC are reduced. As mentioned before, the only study in the current review to use an exhaustive exercise protocol showed no effect in either the young or old participant groups (study # 3). This finding could be partially explained by Diestrich's hypofrontal hypothesis, as exhaustive exercise would be the shortest in duration but highest in intensity. For the HIC and HIIT protocols, there does not appear to be an obvious trend between intensity or duration of exercise and performance on the cognitive tasks assessed. For example, Study #2A used a 10 min HIIT protocol (HI intervals at 70% peak aerobic power) and showed an effect of exercise on inhibition. Study #12 also used a10 min HIIT protocol (HI intervals at 85-90% VO2max) and showed an effect for cognitive flexibility but not for inhibition, WM, or attention. In Study #1A, a 35 min HIIT protocol (HI intervals at 75-85% HRmax) showed an effect for inhibition, cognitive flexibility, and attention. When considering the HIC protocols there was also no obvious pattern to the findings. Study #6 used a 10 min continuous protocol (20% difference between GET and VO2peak) but showed no effect on inhibition or attention, while Study #8, which also used a 10 min HIC protocol (80-85% VO2max) showed an effect of exercise on inhibition, cognitive flexibility, and attention. Unlike the HIIT protocols however, a 35 min HIC protocol at 85-90% HRmax (Study #13) did not show an effect on cognitive flexibility or attention.

It is evident that the underlying processes are more complex that just an increase in arousal or catecholamine concentration. Indeed, growing research has suggested that increased catecholamine concentration only offers a partial explanation for the decrease in cognitive performance observed in some studies and, depending on the task, activation of adrenoceptors has been shown to improve cognitive performance. In a study by Bari and Robbins (2013) it was found that, in rats, α^1 and β1/2-adrenoceptor antagonists impaired stop-signal task performance and sustained attention respectively. Additionally, attentional set-shifting benefits from, and even depends on, activation of α^1-receptor in the medial PFC (mPFC; Robbins and Roberts, 2007; Bondi, Jett, & Morilak, 2010). Attentional set-shifting is a component of cognitive flexibility which requires participants to switch between various stimulus-response sets depending on the specific stimuli they are presented with (Robbins, 2007; Sawada et al., 2012). Considering set-shifting seems to benefit from increased catecholamine activity, and HI exercise increased circulating catecholamines, this would perhaps explain why almost all the extracted studies that tested cognitive flexibility showed an effect. In contrast to other EFs, cognitive flexibility could be uniquely receptive to HI exercise. A related explanation could be that, in general, cognitive tasks that required the least amount of PFC activation would show better performances after heavy exercise compared to tasks that relied more on the PFC. Reaction time, short-term memory, visual search, and simple arithmetic are considered to be tasks that require minimal PFC activity and are more dependent upon attention and alertness (Dietrich & Audiffren, 2011; Rektor et al., 2004). This effect can also be seen within different components of a cognitive task. For example, a meta-analysis by McMorris et al (2010) examined how an acute bout of intermediate intensity exercise

independently affected the speed and accuracy of working memory tasks, finding that there was a beneficial effect of exercise on response time but a significant detrimental effect of exercise on accuracy. An early study led by McMorris (McMorris et al., 2009) also showed that exercise induced-changes in plasma norepinephrine and adrenocorticotropin hormone (ACTH) predicted changes in Flanker response time (RT) whereas changes in plasma epinephrine predicted changes in Flanker error rate.

The takeaway message from the above noted evidence is that exercise intensity and duration exert effects on the neurotrophic factors in the brain, impacting the brain on a cellular and systemic level. Multiple pathways and receptor types are stimulated by exercise, but while the intensity and duration of the exercise is usually the experimental factor, the nature of the cognitive domain and how it is measured can also influence the findings. Additionally, research in the area of cognition has also shown that the cognitive task itself and how it is designed will have an impact on how performance is measured and interpreted.

4.2 Variability of cognitive measures

Within a given cognitive domain, there are numerous tests and/or tasks that can be used, each aiming to selectively target a specific behaviour or component. When it comes to measuring the effect of exercise on cognition, it is important to have valid and reliable measures, but growing evidence suggests that not all tasks, or versions of tasks, are equivalent. The Stroop Task, for example, is a popular task used in research to measure inhibition and has been considered by some to be the "gold standard" of attentional measures (MacLeod, 2002). The Stroop Task was used in seven of the extracted papers in the current review, with each study using their own unique version of the Stroop task.

However, even a test as reliable as the Stroop is subject to large variability depending on the version being used. In his review, MacLeod (1991) highlights this by proposing many factors related to the design of the Stroop task that can impact the interference effect, one of which is modality of response. The two modalities MacLeod focuses on are vocal (naming the responses aloud) and manual (using a keypress), and he explains that the Stroop effect is reduced when the modality is switched from oral to manual. In the current review, none of the Stroop tasks included used the vocalized modality. Instead, all studies used the manual modality, with a split between pencil and paper (studies #1, 3, and 8) and computerized keypresses (studies #2, 13, and 15). Much like vocal vs. keypress, a study by Penner and co-authors (2012) showed that using computerized versions of the Stroop task not only altered the magnitude of the interference effect, but also changed its characteristics.

Penner et al (2012) performed an experiment with 29 children (mean age 11.4) and 40 adults (mean age 25), using three different versions of the Stroop task. The first was the printed color-word task where the colors (red, green, yellow, and blue) were placed on a sheet of paper either as colored dots (neutral) or as a color name (conflict). The color names were never printed in the color they named, creating the conflict. The second was a computerized color-word in which either Xs (neutral condition) colored red, green, blue, or yellow appeared on the screen, or a color name in a different color (conflict condition) appeared. Participants were instructed to press one of four buttons corresponding to the four possible printed colors as quickly as possible. The third was a color-word matching task. Again, Xs (neutral condition) in the colors above or color names (conflict condition) appeared on the screen, followed by a color name printed in

black ink beneath the colored stimuli. Participants had to decide as quickly as possible whether the color name printed in black was the same as the ink color of the stimulus above. The response options were limited to ‘‘yes’’ or ‘‘no’’, which were indicated by a sign on the keyboard.

The authors found that the strongest interference effect was seen in the printed paper version for both children and adults as compared to both computerized versions. What the authors found surprising was that the forced choice color-word matching task actually produced a stronger Stroop effect than the more conventional computerized Stroop task used in the second condition. Indeed, in the conventional computerized version, the Stroop effect was barely present in children. In terms of the color-word matching task, there was high test-retest reliability for both adults and children, but a failure to show a meaningful correlation to the paper Stroop task in adults. Only the two computerized versions showed a correlation with each other. In light of these findings, the authors suggested that the interference effect created by the computerized versions are due to different underlying mechanisms than those recruited by pen and paper versions.

Moreover, in the current review, for each of the studies that did use the Stroop task there was considerable variability in how the data were analyzed to calculate the interference effect score. For example, in Study #1, participants used a paper and pencil Stroop task in which they were instructed to read from a list of words. As soon as a word was highlighted they would say the colour and avoid saying the word. In their analysis, the authors did not calculate an interference effect, rather they reported that the increased number of right choices of pre/post Stroop was indicative of an increase in performance. In contrast, Study #8, which also used a paper and pencil version of the Stroop task,

divided the trials into three conditions: (1) participants read aloud color words printed in black ink (word condition); (2) participants read the name of the colors of Xs printed in different colored ink (color condition); and (3) participants named the colors of incongruent color words presented in different ink colors (color-word condition). In their analysis, the investigators recorded the number of correct answers in 45 seconds for each condition as the score and calculated the Stroop effect by dividing the color-word score by the color score (CW/C). As a final comparison, Study #2 used a computerized version of the Stroop task, but instead of color/word combinations participants were presented with either numeric words (i.e., one, two, or three) or non-numeric, neutral words (e.g., any, great) in various combinations of word sets: congruent (e.g., "two two"), incongruent (e.g., "three three"), or neutral (e.g., "any any"). Stroop performance was represented by the inverse efficiency score, which was calculated by dividing response times (ms) by Stroop Accuracy (%).

Another obstacle in interpreting the results of such cognitive assessments is that certain cognitive tests are intended to measure a wide breadth of cognitive abilities with only a few outcome measures. The ToH task, for example, is considered to be a measure of inhibition, working memory, and fluid intelligence (Zook et al., 2004). In Study #4, the only study included in the review that used the ToH, only two outcome measures were recorded: seconds required to complete the task and total moves. In other studies, a set number of moves may be established by the researchers a-priori and the number of additional moves required of the participant to finish the task can be recorded as a measure of performance (Zook et al., 2004). None of these measures, however, are explicitly dependent on a single cognitive domain and their interpretations require careful

consideration. The Flanker task faces similar problems of interpretation. Typical Flanker outcome measures include reaction time (RT), accuracy (%), and interference scores (sometimes called conflict effect scores) which, like the ToH, are used to infer cognitive performance. Researchers however don't consistently use the same outcome measure to determine performance. In Study #9 for example, performance was measured by calculating a conflict effect score for both RT and accuracy, and improved performance was indicated by a smaller conflict effect score after exercise whereas study #11 used only the difference in RT to determine performance. Considering how different versions of the task and the variation in data analysis and interpretation, it would be beneficial to establish standardized measures of the behaviors being studied and to consistently apply these throughout the field.

4.3 Time dependent differences

This final part of the discussion focuses on a broader area of inconsistency within the research that can be summarized as time-dependent variability. For the purpose of this discussion, time-dependent variability refers to all variables, controlled or not, that relate to time-dependent or time-sensitive mechanisms. Time is an important factor when studying exercise and cognition. Exercise is considered a stressor in the sense that it activates the HPA-axis and sympathetic nervous system to increase cortisol and other energy-mobilizing messengers. The ramping up, maintenance, and then ramping down of the stress response is time sensitive, which therefore makes it a source of time-dependent variability across exercise and cognition studies. The time delay between the end of exercise and the administration of cognitive testing must be tightly controlled if one wishes to take advantage of the increased stress hormones in the participant's system.

According to the meta-analysis conducted by Chang and co-authors (2012), cognitive tests that are administered 11 to 20 min after exercise cessation produced the biggest effect, and these effects diminish following a longer (>20 min) delay. When the studies are plotted based on the exercise/cognition time delay (as shown below in Figure 4), we can see not only that very few of the extracted papers were within the recommended time frame, but also that they don't follow any consistent pattern.

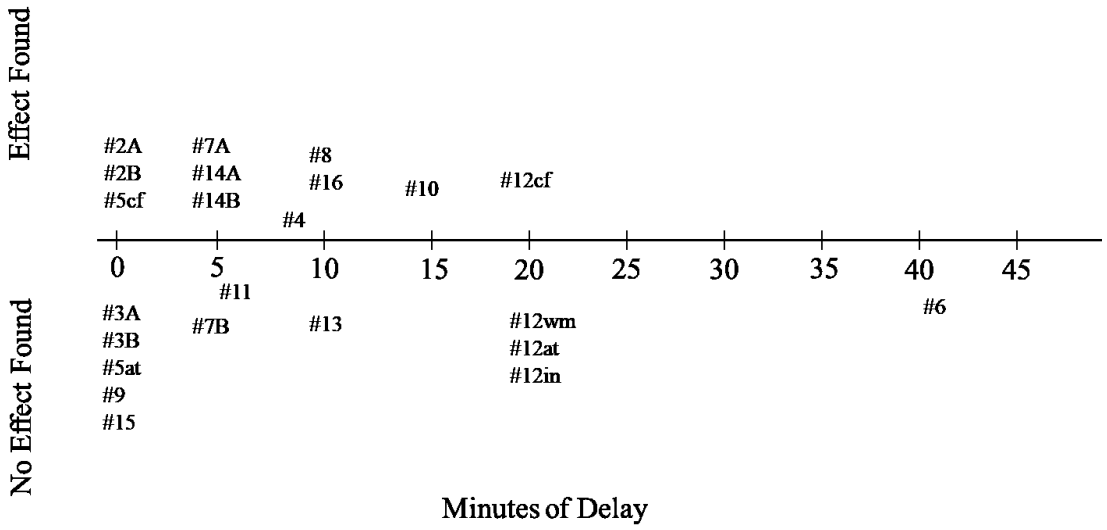

Figure 4. Potential impact of time-delay on presence of an effect. The X-axis depicts the time-delay between exercise and the administration of cognitive tests (min) with the 0-min mark representing tests that were given immediately after exercise with no delay. Studies listed above the x-axis showed an effect of exercise on cognition whereas those listed below the x-axis did not. It should be noted that some studies looked at multiple cognitive domains. If exercise impacted the cognitive domains differently, then each cognitive domain was represented separately beside the study number. CF = cognitive flexibility; AT = attention; WM = working memory; and IN = inhibition. Study #1 is not shown in the figure.

Studies #4, 6, and 11 had the corresponding time delay of 8, 41, and 6 min respectively. It should also be noted that Study #1 is not shown as the cognitive tests were reported to be given once the participant's heart rate returned to resting. Only two studies (#10 and #12) fall within the 11 to 20 min time delay. While there is no obvious pattern between the delay between exercise and administration of cognitive tasks, the

authors of study #6, with a delay time of 41 min, highlighted in their discussion that the failure of exercise to produce an effect on cognition was potentially a result of the long delay between events. It should also be noted that several of the included studies administered the cognitive tests at multiple time points but, for simplicity's sake, only one time point was used in analysis. Studies #2, 3, 5 and 15 all tested at least two different time points post-exercise, though the only common time point shared between all four studies was that of 0-min post, therefore that was the chosen time point that was extracted.

While the Chang et al (2012) paper did not delve into the underlying mechanisms that might be responsible for this optimal time delay, an explanation might be found by examining the stress response. As previously discussed, cortisol levels increase with increased exercise intensity and duration. Once the exercise is stopped, cortisol is slowly removed from circulation via the negative feedback loop that acts through glucocorticoid receptors (GR) to inhibit corticotropin-releasing hormone (CRH) secretion in the hypothalamus. Along with these changes in cortisol levels, one must also take into account the other endocrine and neurochemical factors that are stimulated by exercise. As mentioned in the introduction, neurotrophic factors such as BDNF increase after exercise. In the previously mentioned study performed by Martinez-Diaz et al (2020), male college students performed a bout of HIIT (10 x 1 min) at their VO2 peak power output. Cortisol and plasma BDNF levels were taken pre-, post-, and 30 min post-intervention. It was found that plasma BDNF concentrations rose significantly after exercise but returned to pre-exercise levels within 30 mins post-intervention, whereas cortisol levels progressively increased from pre-exercise to 30 mins after the intervention. Another

important cognition-promoting neurotransmitter that has not been discussed in depth is dopamine. As outlined in their review, Chen et al (2016) explain that cortisol, acting through GRs, upregulates dopamine production in the mPFC. Dopamine helps to regulate cortisol by activating GABAergic neurons in the anterior bed nuclei of the stria terminalis which then projects to the paraventricular nucleus of the hypothalamus to decrease CRH production. In a separate pathway, mPFC GR activation by cortisol facilitates glutamatergic inputs to dopamine neurons in the ventral tegmental area (VTA), which project reciprocally back to the PFC to increase dopamine release in the mPFC. Therefore, as cortisol levels increase with exercise so too does dopamine in the mPFC. This relationship between cortisol and dopamine is relevant to our understanding of how exercise improves cognition. Dopamine is essential for cognitive functions that rely on the PFC, particularly EFs such as working memory, attention, and flexible behaviour (for review see Ott & Nieder, 2019). Unfortunately, there is very little available research on prefrontal dopamine concentrations following exercise. In rodent models of aerobic exercise, striatal dopamine levels have been shown to return to baseline levels within 2 hours (Meeusen et al., 1997), though this timeline depends on the exact protocol being used. Indeed, it is difficult to know the concurrent time course of cortisol and dopamine levels in the mPFC, and whether dopamine levels decrease at the same rate as cortisol, or if dopamine levels are maintained for longer. Nonetheless, research has shown that chronic exercise increases overall dopamine levels in the mPFC while also increasing basal cortisol levels in the body (for review see Chen et al., 2016). It is clear that levels of cortisol and dopamine are closely linked, and their relationship might offer a potential

explanation for the supposed 11-20 min post-exercise time window for administering cognitive tests, though more research is needed.

The role of cortisol on the time-dependent variability of the included studies is not limited to its fluctuation following exercise. Indeed, cortisol follows a 24-hour cycle over the course of the day, contributing to the circadian rhythm of the body. Cortisol increases rapidly in the morning and peaks about 30 to 45 min after waking (Pruessner et al., 1997; Wilhelm et al., 2007). This cortisol awakening response promotes the transition from a state of sleep to that of wakefulness and helps promote cognitive, immune, and behavioural awakening (for review see Clow, Hucklebridge, & Thorn, 2010). Over the course of the day, cortisol levels decline. As was shown in a recent study, cortisol levels show a midday pulse in healthy males following a meal, but then decline until the hours surrounding the onset of sleep where they are the lowest (Bhake et al., 2019). These changing levels of cortisol should not be ignored when designing an experiment that seeks to investigate the effect of exercise on cognition.

In terms of physical performance, research has demonstrated significantly enhanced performance in the evening as compared with the same exercises performed in the morning, and that performance is closely linked to the fluctuation of body temperature with peak physical performance coinciding with the peak in body temperature (for reviews see Teo et al., 2011; Shibata & Tahara, 2014; Duglan & Lamia, 2019). The cortisol response to exercise also changes depending on the time of day. In a study conducted by Bonato et al (2017), the cortisol response following an acute bout of HIIT was studied at different times of the day in participants with different circadian phenotypes. Participants performed the HIIT protocol in the morning (8:00 am) and

evening (8:00 pm) with salivary cortisol samples taken Pre, Post-0, -15, -30, -45, and -60 min after completion of the exercise. In both morning and evening workouts, there was a significant increase in cortisol Post-0 compared to Pre, though this was not found at any other time point. When comparing morning vs evening workouts, across all time points there was significantly higher cortisol levels in the morning than in the evening. These results further demonstrate the circadian rhythm of cortisol in the body, with levels being high in the mornings and decreasing in the evening, but the important takeaway is that even after a bout of HIIT in the evening, cortisol levels did not reach those observed in the morning, including those recorded pre-exercise.

Furthermore, cognitive performance also follows a circadian rhythm. Performance on simple tasks that require less cognitive resources, such as simple serial search tasks, tend to follow the rhythm of core body temperature such that performance peaks in the evening (8:00 pm) whereas more complex cognitive tasks tend to peak earlier in the day around 2 pm (Folkard, 1990). Some studies have even found peak performance of complex tasks to occur from mid- (e.g., short term memory retention; Liard, 1925) to late-morning (e.g., logical reasoning tasks; Folkard, 1979). The reasoning behind this variation in performance has been linked to levels of alertness, which vary across the day in tandem with core body temperature. This cannot be the only explanation as it would therefore be expected that performance on all cognitive tasks, no matter the complexity, would peak at the same time. To account for this, a two-process model of alertness (Folkard & Åkerstedt, 1991; Åkerstedt and Folkard,, 1997) has been proposed which explains that, in parallel with the rhythmic changes in core body temperature that promotes cognitive performance as it rises, there is an accompanying second component

that decreases cognitive performance with increasing time awake. The model also supposed that the relative importance of the two factors depends on the nature of the cognitive task such that complex tasks are more sensitive to time spent awake, and therefore performance deteriorates earlier in the day. It should be reiterated that, while a circadian rhythm of cognitive performance is important to acknowledge, it is one of many factors that influence cognitive functions. Factors altering the circadian rhythm itself must also be controlled before conclusions can be made regarding changes in performance. Factors such as motivation, stress, food intake, posture, ambient temperature, caffeine consumption, physical activity, or lighting conditions are all parameters that can exert a masking effect on the circadian profile of cognitive functions (for review see Schmidt et al., 2007). The term "masking" is applied when any external or internal factor hides or masks the true endogenous rhythms of the body. Other internal factors that are relevant to cognitive function include inter-individual differences in task performance and chronotype, which is the inter-individual differences in one's subjective sleep and wake timing preferences (Roenneberg et al., 2007). As such, when it comes to studies of exercise and cognition, exercise itself is both the experimental variable and also a confounding variable. There is still much to be understood on whether exercise affects cognition differently at different times of the day. The best option for researchers at the moment is to control, or at least keep track of, time related variables. For example, ensuring multi-session experiments are done at approximately the same time of day, keeping track of the daily time range of data collection (e.g., data was collected between 9:00 to 15:00), noting the duration of exercise and the cognitive task, performing statistical analysis with time-of-day as a predictive variable, and finally, tight control over

the time delay between the cessation of exercise and the beginning of the cognitive task(s).

4.4 Conclusion

While there are many more factors that could be discussed to explain the lack of cohesive results found in the current review, they are beyond the scope of this discussion. To review what has been discussed above, plausible factors that may have contributed to the results include the duration and intensity of the exercise, the nature of the cognitive task, levels of BDNF and dopamine (both in terms of promoting and reducing cognitive abilities), cortisol secretion, and time-dependent variables such as the circadian rhythm and the timing of cognitive test administration. Despite rising evidence supporting the importance of these factors when researching exercise and cognition, the majority of studies extracted in this review failed to acknowledge and/or control for them. Typically, the goal of research is to create a body of evidence which allows informed decisions to be made. In the field of exercise and cognition, the results of studies can be used to rehabilitate individuals with trauma induced cognitive impairment, to slow the impact of aging on the brain, and to help individuals with mental disorders such as depression and anxiety to cope with their symptoms. But when such evidence comes from a heterogeneous body of research, questions of the extent of data reliability arise. Future research in this area should aim to create more standardization and control over the previously mentioned time-dependent sources of variability. It would also be beneficial for researchers to consider the broader context of their research. When studying exercise and cognition together, it is easier, though not correct, to assume they can be isolated from the internal, external, and emotional environment of the participants. While not

every factor can be controlled, researchers should aim to inform themselves on relevant evidence that might be outside their typical scope before designing an experiment. Another suggestion would be to reduce the amount of cognitive test variations within the field, or to ensure that the outcome measures of one test variation correlate with the outcome measures of several other popular test variations. With these recommendations put in place, a more homogeneous and reliable connection between exercise and cognition can be revealed. Until then, investigators should practice caution when conducting meta-analysis, reviews, or when synthesizing results from multiple studies as not all studies are comparable.

4.5 Limitations

There are several limitations that must be considered when drawing conclusions from the results. As with all scoping reviews, there is a risk of selection bias if certain key words or phrases were not used in the initial search. Additionally, scoping reviews do not assess the quality of the extracted studies. As long as the studies meet the criteria then they are included, regardless of quality. Another related limitation is the need for specific exclusion criteria. Particularly the criteria of only accepting studies that used cycling or treadmill based exercises which excluded an area of research that investigates more untraditional or recreational forms of aerobic exercise (e.g., Zumba or organized sports). While this criterion did limit the diversity of exercise protocols, it was necessary in order to facilitate the comparison between studies. Additionally, only studies with healthy adult samples were included which greatly reduced the number of extracted studies. This criterion was, however, also necessary in order to ensure there were no factors, other than exercise, affecting cognitive performance.

Study homogeneity is another limitation that is common to scoping reviews and is an issue that has been deeply explored in the discussion and therefore will only be briefly mentioned here. The variabilities of cognitive tests, exercise intensities, data analysis, and time management of cognitive test administration make the comparison of results challenging and, at times, impossible.

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Appendix A

MY

EBSCOhost

Wednesday, July 29, 2020 2:05:28 AM

#	Query	Limiters/Expanders	Last Run Via	Results
S24	S3 AND S11 AND S23	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - CINAHL with Full Text	126
S23	S12 OR S13 OR S22	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - CINAHL with Full Text	15,016
S22	S14 AND S21	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - CINAHL with Full Text	5,753
S21	S15 OR S16 OR S17 OR S18 OR S19 OR S20	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - CINAHL with Full Text	364,087
S20	TI (physical* N5 (fit* OR activ* OR movement* OR train* OR condition* OR program*)) OR AB (physical* N5 (fit* OR activ* OR movement* OR train* OR condition* OR program*))	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - CINAHL with Full Text	81,561
S19	TI ((weight* OR strength* OR enduranc* OR circuit* OR interval) N5 (program* OR train* OR session*))	Expanders - Apply related words; Apply equivalent subjects	Interface - EBSCOhost Research Databases Search Screen - Advanced Search	21,864

	OR AB ((weight* OR strength* OR enduranc* OR circuit* OR interval) N5 (program* OR train* OR session*))	Search modes - Boolean/Phrase	Database - CINAHL with Full Text	
S18	TI (run* OR jog* OR sprint* OR treadmill* OR row* OR bicycl* OR cycl*) OR AB (run* OR jog* OR sprint* OR treadmill* OR row* OR bicycl* OR cycl*)	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - CINAHL with Full Text	140,721
S17	TI (exercis* OR sport* OR fitness* OR gym* OR aerobic*) OR AB (exercis* OR sport* OR fitness* OR gym* OR aerobic*)	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - CINAHL with Full Text	177,828
S16	(MH "Aerobic Exercises")	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - CINAHL with Full Text	6,814
S15	(MH "Cycling") OR (MH "Running+")	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - CINAHL with Full Text	21,276
S14	TI (high N2 (intensity OR impact)) OR AB (high N2 (intensity OR impact))	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - CINAHL with Full Text	12,473
S13	TI high intensity exercise OR AB high intensity exercise	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - CINAHL with Full Text	2,141
S12	(MH "High-Intensity	Expanders - Apply related	Interface - EBSCOhost	11,264

	Interval Training") OR (MH "Exercise Intensity")	words; Apply equivalent subjects Search modes - Boolean/Phrase	Research Databases Search Screen - Advanced Search Database - CINAHL with Full Text	
S11	S4 OR S5 OR S6 OR S7 OR S8 OR S9 OR S10	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - CINAHL with Full Text	418,261
S10	TI (working memory OR inhibition OR inhibitory control OR attention OR emotion regulation OR self monitoring OR self control OR initiation OR planning OR flexibility OR organization) OR AB (working memory OR inhibition OR inhibitory control OR attention OR emotion regulation OR self monitoring OR self control OR initiation OR planning OR flexibility OR organization)	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - CINAHL with Full Text	385,480
S9	(MH "Self Regulation+")	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - CINAHL with Full Text	6,084
S8	(MH "Attention")	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - CINAHL with Full Text	16,079
S7	(MH "Memory, Short Term")	Expanders - Apply related words; Apply equivalent subjects	Interface - EBSCOhost Research Databases Search Screen - Advanced Search	4,177

		Search modes - Boolean/Phrase	Database - CINAHL with Full Text	
S6	TI (cognitive N2 (flexibility OR inhibition OR performance)) OR AB (cognitive N2 (flexibility OR inhibition OR performance))	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - CINAHL with Full Text	8,592
S5	TI ((cognitive OR executive) N2 (control OR function)) OR AB ((cognitive OR executive) N2 (control OR function))	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - CINAHL with Full Text	23,525
S4	(MH "Executive Function")	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - CINAHL with Full Text	4,289
S3	S1 OR S2	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - CINAHL with Full Text	49,815
S2	TI ((single or one or acute) N3 (session or event or bout or exercise or training or dose)) OR AB ((single or one or acute) N3 (session or event or bout or exercise or training or dose))	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - CINAHL with Full Text	49,401
S1	TI (acute exercise or acute bout) OR AB (acute exercise or acute bout)	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - CINAHL with Full Text	2,808

Appendix A. CINAHL search strategy. July 29, 2020.

Appendix B

Embase®

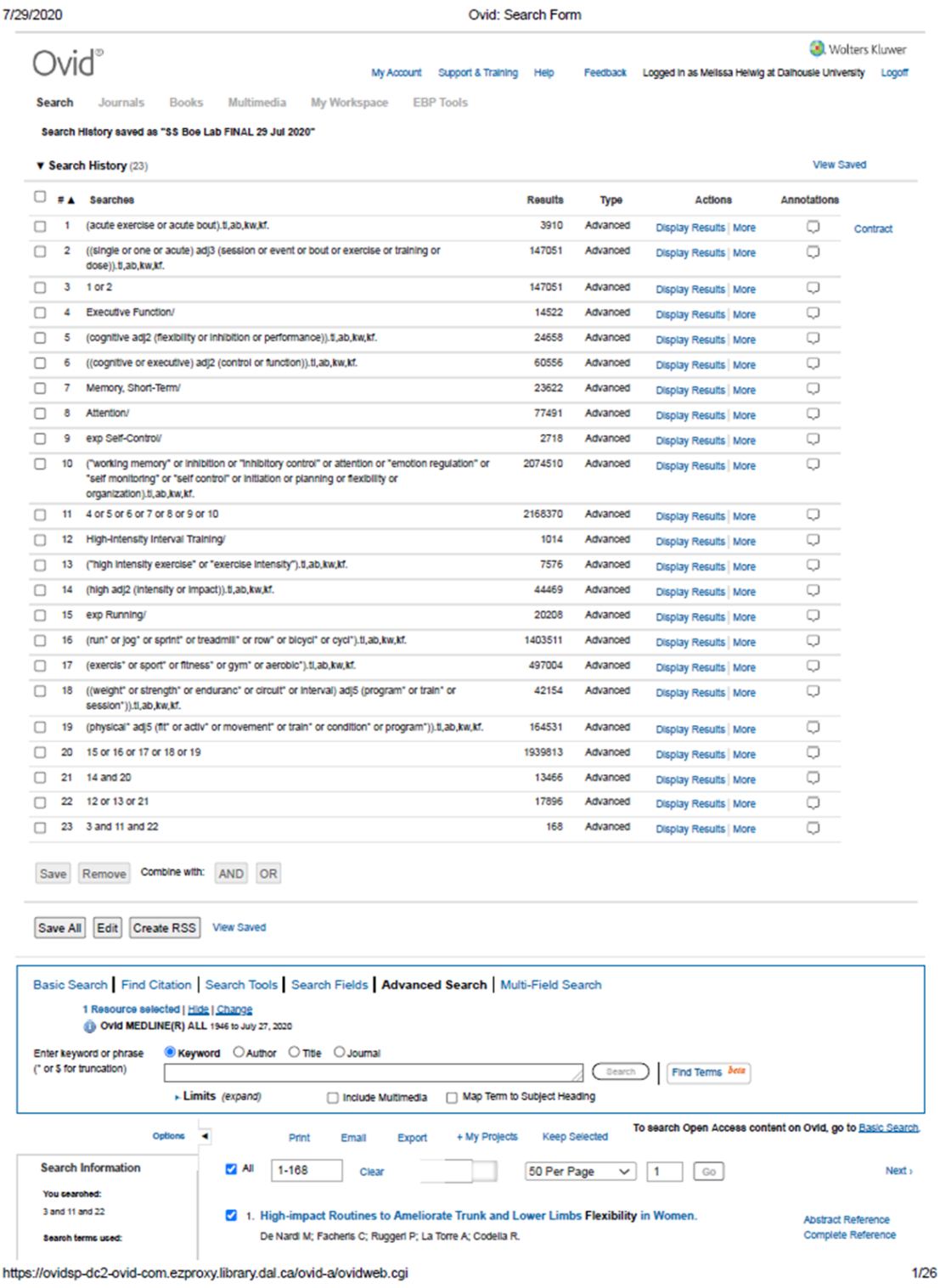
Embase Session Results

No.	Query	Results
#24	#3 AND #11 AND #23	284
#23	#12 OR #13 OR #14 OR #22	25,954
#22	#15 AND #21	16,812
#21	#16 OR #17 OR #18 OR #19 OR #20	2,472,466
#20	(physical* NEAR/5 (fit* OR activ* OR movement* OR train* OR condition* OR program*)):ab,ti,kw	222,180
#19	((weight* OR strength* OR enduranc* OR circuit* OR interval) NEAR/5 (program* OR train* OR session*)):ab,ti,kw	55,323
#18	exercis*:ab,ti,kw OR sport*:ab,ti,kw OR fitness*:ab,ti,kw OR gym*:ab,ti,kw OR aerobic*:ab,ti,kw	641,332
#17	run*:ab,ti OR jog*:ab,ti OR sprint*:ab,ti OR treadmill*:ab,ti OR row*:ab,ti OR bicycl*:ab,ti OR cycl*:ab,ti	1,775,351
#16	'cycling'/exp OR 'running'/exp OR 'jogging'/exp OR 'aerobic exercise'/exp	57,798
#15	(high NEAR/2 (intensity OR impact)):ti,ab,kw	56,565
#14	'exercise intensity'/exp	10,588
#13	'high intensity interval training'/exp	2,270
#12	'high intensity exercise'/exp	46
#11	#4 OR #5 OR #6 OR #7 OR #8 OR #9 OR #10	2,844,649
#10	attention:ti,ab,kw OR 'emotion regulation':ti,ab,kw OR 'self monitoring':ti,ab,kw OR 'self control':ti,ab,kw OR initiation:ti,ab,kw OR planning:ti,ab,kw OR flexibility:ti,ab,kw OR organization:ti,ab,kw	1,535,569
#9	'attention'/exp OR 'emotion regulation'/exp OR 'self control'/exp	255,501
#8	inhibition:ti,ab,kw OR 'inhibitory control':ti,ab,kw	1,104,197
#7	(cognitive NEAR/2 (flexibility OR inhibition OR performance)):ti,ab,kw	34,858
#6	'working memory'/exp OR 'working memory':ti,ab,kw	51,611
#5	((cognitive OR executive) NEAR/2 (control OR function)):ti,ab,kw	87,367
#4	'executive function'/exp	40,037
#3	#1 OR #2	208,400
#2	((single OR one OR acute) NEAR/3 (session OR event OR bout OR exercise OR training OR dose)):ti,ab,kw	208,397
#1	'acute exercise'/exp OR 'acute exercise':ti,ab,kw OR 'acute bout':ti,ab,kw	4,769

ELSEVIER

Appendix B. Embase search strategy. July 29, 2020.

Appendix C



Appendix C. Medline search strategy. July 29, 2020.

Appendix D

MY

EBSCOhost

Wednesday, July 29, 2020 1:20:21 AM

#	Query	Limiters/Expanders	Last Run Via	Results
S21	S6 AND S19 AND S20	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - APA PsycInfo	194
S20	TI ((single OR one OR acute) N3 (session OR event OR bout OR exercise OR training OR dose)) OR AB ((single OR one OR acute) N3 (session OR event OR bout OR exercise OR training OR dose))	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - APA PsycInfo	42,912
S19	S10 OR S11 OR S18	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - APA PsycInfo	3,081
S18	S12 AND S17	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - APA PsycInfo	1,445
S17	S13 OR S14 OR S15 OR S16	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - APA PsycInfo	267,164
S16	TI (physical* N5 (fit* OR activ* OR movement* OR train* OR condition* OR program*)) OR AB (physical* N5 (fit* OR activ* OR movement* OR	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - APA PsycInfo	53,383

	train* OR condition* OR program*))			
S15	TI ((weight* OR strength* OR enduranc* OR circuit* OR interval) N5 (program* OR train* OR session*)) OR AB ((weight* OR strength* OR enduranc* OR circuit* OR interval) N5 (program* OR train* OR session*))	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - APA PsycInfo	13,145
S14	TI (run* OR jog* OR sprint* OR treadmill* OR row* OR bicycl* OR cycl*) OR AB (run* OR jog* OR sprint* OR treadmill* OR row* OR bicycl* OR cycl*)	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - APA PsycInfo	118,677
S13	TI (exercis* OR sport* OR fitness* OR gym* OR aerobic*) OR AB (exercis* OR sport* OR fitness* OR gym* OR aerobic*)	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - APA PsycInfo	111,749
S12	TI (high N2 (intensity OR impact)) OR AB (high N2 (intensity OR impact))	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - APA PsycInfo	7,148
S11	TI exercise intensity OR AB exercise intensity	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - APA PsycInfo	2,227
S10	TI (high intensity exercise OR high intensity interval training) OR AB (high intensity exercise OR high intensity interval training)	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - APA PsycInfo	639
S9	S7 OR S8	Expanders - Apply related words; Apply equivalent subjects	Interface - EBSCOhost Research Databases Search Screen - Advanced	42,993

		Search modes - Boolean/Phrase	Search Database - APA PsycInfo	
S8	TI ((single OR one OR acute) N3 (session OR event OR bout OR exercise OR training OR dose)) OR AB ((single OR one OR acute) N3 (session OR event OR bout OR exercise OR training OR dose))	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - APA PsycInfo	42,912
S7	TI (acute exercise OR acute bout) OR AB (acute exercise OR acute bout)	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - APA PsycInfo	1,230
S6	S1 OR S2 OR S3 OR S4 OR S5	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - APA PsycInfo	745,159
S5	TI (working memory OR inhibition OR inhibitory control OR attention OR emotion regulation OR self monitoring OR self control OR initiation OR planning OR flexibility OR organization) OR AB (working memory OR inhibition OR inhibitory control OR attention OR emotion regulation OR self monitoring OR self control OR initiation OR planning OR flexibility OR organization)	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - APA PsycInfo	662,207
S4	TI (cognitive N2 (flexibility OR inhibition OR performance)) OR AB (cognitive N2 (flexibility OR inhibition OR performance))	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - APA PsycInfo	23,938

S3	TI ((cognitive OR executive) N2 (control OR function)) OR AB ((cognitive OR executive) N2 (control OR function))	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - APA PsycInfo	59,600
S2	DE "Short Term Memory"	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - APA PsycInfo	26,386
S1	(((DE "Executive Function") OR (DE "Cognitive Flexibility")) OR (DE "Attention")) OR (DE "Emotional Control")	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - APA PsycInfo	94,167

Appendix D. PsycINFO search strategy. July 29, 2020.

Appendix E

NY

EBSCOhost

Wednesday, July 29, 2020 1:32:21 AM

#	Query	Limiters/Expanders	Last Run Via	Results
S18	S4 AND S7 AND S17	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - SPORTDiscus	169
S17	S8 OR S9 OR S16	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - SPORTDiscus	17,135
S16	S10 AND S15	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - SPORTDiscus	9,258
S15	S11 OR S12 OR S13 OR S14	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - SPORTDiscus	734,835
S14	TI (physical* N5 (fit* OR activ* OR movement* OR train* OR condition* OR program*)) OR AB (physical* N5 (fit* OR activ* OR movement* OR train* OR condition* OR program*))	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - SPORTDiscus	85,769
S13	TI ((weight* OR strength* OR enduranc* OR circuit* OR interval) N5 (program* OR train* OR session*)) OR AB ((weight* OR strength* OR enduranc* OR circuit* OR interval)	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - SPORTDiscus	37,012

	N5 (program* OR train* OR session*))			
S12	TI (run* OR jog* OR sprint* OR treadmill* OR row* OR bicycl* OR cycl*) OR AB (run* OR jog* OR sprint* OR treadmill* OR row* OR bicycl* OR cycl*)	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - SPORTDiscus	228,248
S11	TI (exercis* OR sport* OR fitness* OR gym* OR aerobic*) OR AB (exercis* OR sport* OR fitness* OR gym* OR aerobic*)	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - SPORTDiscus	516,170
S10	TI (high N2 (intensity OR impact)) OR AB (high N2 (intensity OR impact))	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - SPORTDiscus	10,835
S9	TI exercise intensity OR AB exercise intensity	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - SPORTDiscus	12,006
S8	TI (high intensity exercise OR high intensity interval training) OR AB (high intensity exercise OR high intensity interval training)	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - SPORTDiscus	4,976
S7	S5 OR S6	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - SPORTDiscus	24,644
S6	TI ((single OR one OR acute) N3 (session OR event OR bout OR exercise OR training OR dose)) OR AB ((single OR one OR acute) N3 (session OR event OR	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - SPORTDiscus	24,134

	bout OR exercise OR training OR dose))			
S5	TI (acute exercise OR acute bout) OR AB (acute exercise OR acute bout)	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - SPORTDiscus	4,427
S4	S1 OR S2 OR S3	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - SPORTDiscus	117,554
S3	TI (working memory OR inhibition OR inhibitory control OR attention OR emotion regulation OR self monitoring OR self control OR initiation OR planning OR flexibility OR organization) OR AB (working memory OR inhibition OR inhibitory control OR attention OR emotion regulation OR self monitoring OR self control OR initiation OR planning OR flexibility OR organization)	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - SPORTDiscus	113,485
S2	TI (cognitive N2 (flexibility OR inhibition OR performance)) OR AB (cognitive N2 (flexibility OR inhibition OR performance))	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - SPORTDiscus	2,410
S1	TI ((cognitive OR executive) N2 (control OR function)) OR AB ((cognitive OR executive) N2 (control OR function))	Expanders - Apply related words; Apply equivalent subjects Search modes - Boolean/Phrase	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - SPORTDiscus	4,328

Appendix E. SportsDiscus search strategy. July 29, 2020.

Appendix F

Table 8: Outcome Measures of Inhibition

Study ID	Condition	Outcome Measure **Test**: *Outcome*	G	Effect
Aguirre-Loaiza et al (2019)				
	Physically Active	**Stroop A:** *Response Accuracy*	0.76	Yes
		Response time	0.49	Yes
		Stroop B: *Response Accuracy*	0.25	Yes
		Response time	0.35	Yes
	Physically Inactive	**Stroop A:** *Response Accuracy*	0.97	Yes
		Response time	0.72	Yes
		Stroop B: *Response Accuracy*	0.04	No
		Response time	0.27	Yes
Brown et al (2018)				
	High	**Stroop:** *Efficiency score*		

	Intensity	*(0 min post AE)*	0.35	No
	Interval	*(10 mins post AE)*	0.64	Yes
	Exercise			
		Stroop: *Efficiency score*		
	High	*(0 min post)*	0.44	Yes
	Intensity	*(10 mins post)*	0.41	Yes
	Continuous			
Coco et al (2020)				
		Stroop: *Interference score*		
	Young	*(0 min post)*	1.47	Yes
		(15 min post)	0.11	No
		Stroop: *Interference score*		
	Older	*(0 min post)*	3.83	Yes
		(15 min post)	3.35	Yes
Du Rietz et al (2019)				
		Erikson Flanker:		
		Reaction Time Variability		
		(incongruent)	0.27	No
		Errors (incongruent)	0.19	No
Heath et al (2018)				
	Heavy (15% of the difference	**Antisaccade:**		

	between LT and VO2 peak)	*Percent frequency of RT (ms)*	0.22	No
		Antisaccade:		
	Very Heavy (50% of the difference between LT and VO2 peak)	*Percent frequency of RT (ms)*	0.17	No
Hwang et al (2016)				
		Stroop: *Interference*	0.49	Yes
Ligeza et al (2018)				
		Flanker:		
		Conflict effect response time	0.16	No
		Response Accuracy	0.18	No
Mehren et al (2019)				
		Flanker:		
		Interference score	0.10	No
		Go/No-Go:		
		Sensitivity index	0.1	No
		Correct inhibition rate	0.01	No
Oberste et al (2016)				
		Stroop: *Interference*	0.27	No
Tsukamoto et al (2016)				
		CWST:		

	RT Post-0 mins	0.75	Yes
	RT Post 10 mins	0.62	Yes
	RT Post 20 mins	0.53	Yes
	RT Post 30 mins	0.46	Yes
	CWST:		
	Response Accuracy 0 mins	0.76	Yes
	Response Accuracy 10 mins	0.80	Yes
	Response Accuracy 20 mins	0.67	Yes
	Response Accuracy 30 mins	0.51	Yes
Zimmer et al (2016)			
	Stroop:		
	Stroop Effect	0.27	No
	Reverse Stroop Effect	0.45	Yes

Table 9: Outcome Measures of Attention

Study ID	Condition	Outcome Measure **Test**: *Outcome*	G	Effect
Aguirre-Loaiza et al (2019)				
	Physically Active	**TMT-A:** *Seconds*	0.91	Yes
	Physically Inactive	**TMT-A:** *Seconds*	1.29	Yes
Córdova et al (2009)				
	90% AT	**TMT-A:** *Seconds*	0.42	Yes
Del Giorno et al (2010)				
		Contingent continuous performance: *False Alarms (0 mins post)*	0.0	No
		False Alarms (20 mins post)	0.09	No
Du Rietz et al (2019)				
		Flanker:		
		Errors (incongruent)	0.19	No
		Mean RT (incongruent)	0.18	No
Hwang et al (2016)				

	TMT-A: *Seconds*	0.63	Yes
Ligeza et al (2018)			
	Flanker: *Response Time (incongruent)*	0.08	No
Mehren et al (2019)			
	Flanker: *Reaction Time (Incongruent)*	0.30	No
Moriarty et al (2019)			
	NIH-Flanker	0.2	No
Oberste et al (2016)			
	TMT-A: *Seconds*	0.13	No

Table 10: Outcome measures of Cognitive flexibility

Study ID	Condition	Outcome Measure **Test**: *Outcome*	G	Effect
Aguirre-Loaiza et al (2019)				
	Physically	**TMT-B:**	0.71	Yes
	Active	*Seconds*		
	Physically	**TMT-B:**	0.28	No
	Inactive	*Seconds*		
Córdova et al (2009)				
		TMT-B:	0.26	No
	90% AT	*Seconds*		
Del Giorno et al (2010)				
		Word Colour Stroop		
		Task:	0.22	No
		Total Errors (0 mins post)		
		Total Errors (20 mins Post)	0.11	No
		Perseverative Errors (0		
		mins post)	0.55	Yes
		Perseverative Errors (20		

	mins post)	0.22	No
	Unique Errors (0 mins post)	0.18	No
	Unique Errors (20 mins post)	0.09	No
Hwang et al (2016)			
	TMT-B:		
	Seconds	0.80	Yes
Loprinzi & Kane (2015)			
	TMT-B:		
	Seconds	0.24	No
Moriarty et al (2019)			
	NIH-Fluid cognition	0.23	No
	NIH-Card Sort	0.48	Yes
Oberste et al (2016)			
	TMT-B:		
	Seconds	0.08	No

Table 11: Outcome Measures of Working Memory

Study ID	Condition	Outcome Measure **Test**: *Outcome*	G	Effect
Córdova et al (2009)				
	90% AT	**Tower of Hanoi:**		
		Number of moves	0.59	Yes
		Seconds to completion	0.37	No
Moriarty et al (2019)				
		NIH-Working memory	0.10	No