6-25-2020 12:00 PM

Understanding the Effects of Physical Activity on Executive Functioning and Psycho-Emotional Well-Being in Children with ADHD

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A thesis submitted in partial fulfillment of the requirements for the Master of Arts degree in Education

Abstract

A short bout of physical exercise has been shown to improve executive functioning in children. However, the implications for children with Attention Deficit Hyperactivity Disorder (ADHD) has been understudied. We examined the impact of a 10min bout of physical exercise on executive functioning and psycho-emotional well-being in children with ADHD. Participants engaged in two lab-based sessions separated by 1-week: a physical exercise session and a control session. The physical exercise session included a 10min bout of moderate-intensity biking, with a pre-post battery of cognitive and psycho-emotional assessments. The control session consisted of 10mins of silent reading. We used functional imaging during the cognitive assessments to measure changes in prefrontal cortical activation. We found that 10mins of physical exercise promoted greater inhibitory control, positive mood, and general self-efficacy compared to control. This is the first study to our knowledge to examine the effects of an acute 10-minute bout of physical exercise on the impact of executive functioning and psycho-emotional well-being, while simultaneously examining the underlying neural mechanisms associated with these changes. These findings suggest that a short bout of physical exercise has the potential to improve specific aspects of ADHD symptomology.

Keywords

Physical Exercise

Attention Deficit Hyperactivity Disorder

Cognition

Executive Functioning

Functional Near Infrared Spectroscopy

Inhibition

Mood

Prefrontal Cortex

Psycho-Emotional

Self-Efficacy

Summary for Lay Audience

ADHD is the most common neurodevelopmental disorder in children, affecting approximately 6% of Canadian school-aged children. ADHD is characterized by deficits in executive functioning, including sustained attention, inhibitory control, and working memory, ultimately interfering with academic success and every-day functioning. Several efficacious treatment methods exist to diminish these deficits, such as pharmacological treatments and behavioural management treatments, yet they all have significant shortcomings, such as exacerbating mood disturbances and/or being inaccessible to those of lower socioeconomic status. Physical exercise has been identified as a potential supplementary intervention for ADHD to help ameliorate symptoms. The majority of research in this area has focused on the impact of chronic physical exercise interventions (i.e., weeks- or months-long) as well as longer sessions (20 mins-hour) to ameliorate ADHD deficits. Little work, however, has been devoted to understanding how a short (10 min) acute physical exercise bout (i.e., a single session) impacts the neurocognitive and psycho-emotional functioning of children with ADHD. This thesis aimed to address these gaps by 1) investigating the impact of a single physical exercise bout on the executive functioning of children with ADHD; 2) investigating how a single physical exercise bout impacts the attention-center of the brain (i.e., prefrontal cortex) and corresponding executive functions using neuroimaging; and 3) examining how a single session of physical exercise impacts psycho-emotional functioning such as self-efficacy, mood, motivation and affect. Participants aged 10-14 with ADHD engaged in two lab-based sessions separated by 1-week: a physical exercise session and a control session. The physical exercise session included a 10min bout of moderate-intensity biking, with a pre-post battery of cognitive and psycho-emotional assessments. The control session consisted of

10mins of silent reading. We used functional neuroimaging during the cognitive assessments to measure changes in brain activation within the prefrontal cortex. We found that 10mins of physical exercise promoted greater inhibitory control, positive mood, and self-efficacy compared to silent reading. This information could increase the accessibility of physical exercise interventions to support children with ADHD, especially in terms of cost and time, as the extant long-term interventions tend to be lengthy and costly.

Acknowledgements

I would like to thank my supervisor Dr. Fenesi for her guidance and mentorship throughout this project. Your constant encouragement has allowed me to achieve goals I thought were unreachable. Your dedication to supporting your students in not just academia but all areas of life is truly admirable. I am forever grateful to have learned from the best and look forward to continuing to learn from you.

Many thanks to my research partner and friend, Marcus Gottlieb. Your thought-provoking questions and reassurance throughout our project was greatly appreciated.

My utmost gratitude to my family and friends. Thank you to my parents, who have always been by my side, providing unconditional love and support while always encouraging me to pursue my goals. Our daily phone calls and texts gave me constant reassurance throughout this project. Thank you to my brother Logan who has been by my side throughout my personal and academic life. I am truly thankful for your tough love. Most importantly, I would like to thank my partner Tyler for his undying love, support, and encouragement. I am so thankful for the time invested in reviewing and editing my writing- you know the ins and outs of this thesis. I could not have done this without you.

I would like to express the deepest appreciation to my committee members Dr. Friesen, Dr. Brown and Dr. Prapavessis. I truly appreciate your guidance and time.

Finally, thank you to the participants who made this project possible.

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Chapter 1: Introduction

1.1 Statement of the Problem

Attention Deficit Hyperactivity Disorder (ADHD) is one of the most common neurodevelopmental disorders and affects many aspects of a child's life (Furman, 2005; Polanzyk et al., 2007). ADHD is characterized by cognitive deficits affecting the domain of executive functioning, including impaired inhibitory control, flexible task switching, sustained attention, and working memory (Bull and Sceif, 2001; O'Malley, 2011). These deficits in executive functioning can affect children's academic and social functioning and can interfere with their overall quality of life. Pharmacological interventions are the most common treatments available but have notable limitations such as headaches, sleep interruption, and mood disturbances. Pharmacological interventions also often fail to support students' ability to do well in school (Kidwell et al., 2015; Zachor et al., 2006). Given these limitations, parents and researchers are searching for safe, effective alternative treatment options. The current research aimed to gain a more comprehensive understanding of how physical exercise can be used as a potential alternative or supplementary intervention to support executive functioning and psycho-emotional well-being in children with ADHD.

1.2 Summary of Study

Engaging in physical exercise has been shown to ameliorate many of the cognitive deficits associated with ADHD, such as inattention, hyperactivity, and memory deficits (Verret, 2012). Not only do long-term physical exercise interventions (2-8 weeks) improve these cognitive deficits, but a single 10-20 minute bout of physical exercise has been shown to have immediate positive effects on the same cognitive functions (Grassmann et al., 2017). In order to further understand how physical exercise can benefit cognitive deficits associated with ADHD, the current thesis aimed to provide additional evidence for the role of a single, short bout of physical exercise on executive functioning in children with ADHD. We also aimed to better understand how a short bout of physical exercise impacts the attention-center of the brain, i.e., prefrontal cortex (PFC), and the corresponding impact on executive functioning. Finally, we aimed to examine how a single bout of physical exercise not only impacts neurocognitive functioning but also psycho-emotional functioning such as self-efficacy, mood, motivation, and affect. The following introduction will discuss executive functioning and its link to ADHD, current alternative treatment options for treating ADHD, including physical exercise, the current state of research on the effects of physical exercise on executive functioning and PFC functioning in individuals with ADHD, the role of physical exercise on psycho-emotional functioning in individuals with ADHD, and how the current study aimed to address gaps in the literature.

1.3 Attention Deficit Hyperactivity Disorder (ADHD) and Executive Functioning

ADHD affects approximately 6% of children worldwide (Furman, 2005; Polanzyk et al., 2007). This neurodevelopmental disorder is characterized by pervasive and impairing symptoms of inattention, hyperactivity, and impulsivity, interfering with both functioning and normal development (Matte et al., 2015). ADHD is highly comorbid with an array of disorders, and is associated with many developmental, social, health, lifestyle, and emotional impairments (Barkley, 2002). Due to these various impairments, the educational and future occupational outcomes for children with ADHD are largely impacted (Kuriyan et al., 2013). Much research has been conducted in an attempt to understand the underlying etiology of ADHD and factors influencing academic struggle. Reduced academic success in children with ADHD has been linked to impairments in executive functioning (Johnson & Reid, 2011), most specifically during tasks requiring sustained attention, inhibitory control, flexible task switching, and working memory (Bull and Sceif, 2001; O'Malley, 2011).

Sustained attention is the ability to direct and maintain focus on specific stimuli. (Christakou et al., 2013). Tasks of sustained attention often require that a participant view and respond to target stimuli over a period of time. Children with ADHD often show deficits in performance over the duration of tasks of sustained attention, making multiple errors, and omissions (O'Connell et al., 2004). Sustained attention is required for successful functioning during everyday tasks but is especially crucial for performance in academics, particularly in following instructions, maintaining focus during classroom instruction, and completing learning tasks (Tucha et al., 2015; Ko et al., 2017).

Inhibitory control is a critical element for successfully suppressing preplanned dominant, automatic, or habitual responses (Munakata et al., 2011). Impulsivity, defined as a lack of inhibitory control, is associated with an inability to filter out distracting information and withhold behaviours not appropriate for a given situation (Slusarek, 2001). In tasks of inhibition, participants are required to ignore certain stimuli while lending attention to others. In various neuropsychological tasks of inhibitory control, children with ADHD make significantly more errors withholding incorrect responses, display slower reaction times, and have highly variable response patterns when compared to healthy age-matched controls (Bohlin et al., 2004). Inhibitory control is required in order to listen to and follow instructions, remain focused, and is crucial in language development (Daley & Birchwood, 2010).

Task switching is also often impaired among children with ADHD and reflects the ability to shift attention from one task to another (Yeung & Monsell, 2003). In order to effectively switch from one task to another, a previously active task-set must be ignored in favour of the new task set (King, 2007). Tests that use task switching require participants to focus on one set of rules, then shift to a second set of rules. Children with ADHD struggle with inhibiting irrelevant information when switching from one task to another, leading to significantly more errors in task-switching tests when compared to typically developing children (Cepeda et al., 2001). Task switching is necessary for a variety of cognitively demanding tasks and academic domains such as mathematics, reading, and writing (Clark et al., 2010).

Working memory consists of the maintenance, manipulation, and storage of information in mind (Klingberg et al., 2005). Working memory is used when a person is required to hold information in mind for a short period of time to then be used for some purpose, such as remembering a set of numbers to be recalled (Tannock et al., 1995). Children and adults with ADHD show decreased performance on working memory assessments, as well as a decrease in neural activation in brain regions associated with working memory function (Schecklman et al., 2009). Working memory is essential for completing many cognitive tasks, remembering instructions, reading, and writing (Engle, 2002).

Taken all together, these cognitive processes facilitate the ability to successfully interact with a changing environment and are central to learning success throughout development and quality of life through adulthood (Cotrena, 2016). Impairments in executive functioning can lead to poor focus and planning, the inflexibility of thinking, and difficulty implementing strategies to solve dynamic problems; most, if not all, of these impairments, are displayed by individuals with ADHD and can impact their life success (Ziereis and Jansen, 2015).

1.4 Prefrontal Cortex, Executive Functioning and ADHD

Engaging in tasks that require executive functioning has been consistently shown to increase brain activity in the PFC (Konishi et al., 1998). The PFC is known to support a wide variety of executive functioning, including attention, cognitive flexibility, working memory, judgement, and planning (Carpenter et al., 2000). Individuals with damage to their PFC display a plethora of behavioural and cognitive impairments, including forgetfulness, distractibility, emotional instability, locomotor hyperactivity, and difficulty with resolving stimulus conflict (Devinsky et al., 1995). Unsurprisingly, there are many similarities between ADHD symptomology, and those produced by lesions or injuries to the PFC. Imaging studies have shown reduced PFC volume and task-evoked activity in children diagnosed with ADHD (Amsten & Li, 2005; Zhang et al., 2007). These imaging studies are functionally supported by reports of impaired performance on tasks of inhibition, working memory, and task switching in this population (Pauli-Pott et al., 2011). Recently, studies have shown that PFC blood flow is significantly reduced in children with ADHD, providing further evidence that PFC dysfunction may be central to the executive functioning impairments observed in ADHD (Kim et al., 2002).

1.5 Pharmacotherapy and ADHD

The first-line treatment for children with ADHD is pharmacotherapy, currently being used by approximately 60% of ADHD diagnosed Canadian children (Brault, 2012; Shier et al., 2013). Of these pharmacological treatment options, stimulants such as methylphenidate and amphetamines are the most often prescribed. The reason stimulants are thought to be helpful for ADHD symptomology is because they elicit the release of monoamines such as norepinephrine and dopamine throughout the brain (Shier et al., 2013). These monoamines, in part, help to upregulate neural activity, especially within the PFC—the region most often impaired in ADHD (Epstein et al., 2006). Though teachers report a decrease in behavioural issues in children with ADHD who take stimulants, censuses have shown that medication does not improve academic performance or psycho-emotional wellbeing (Currie et al., 2016). Additionally, approximately

30% of individuals with ADHD are known as “non-responders” and do not show cognitive or behavioural improvements with stimulant medications (Hechtman & Greenfield, 2003). When stimulant medications are effective, doses often need to be progressively increased for optimal success, potentially leading to eventual tolerance and resistance (Hechtman & Greenfield, 2003). Stimulant medications also come with various side effects that include sleep disturbances, decreased appetite, delayed growth, headaches and stomach-aches, tics, and increased heart rate and irritability (Kidwell et al., 2015; Zachor et al., 2006). Although stimulants can be effective in managing ADHD in some children, adverse effects, lack of long-term improvement, and adherence support the need for alternative, complementary treatments for ADHD (Pontifex et al., 2013).

1.6 Neuronal Underpinnings of the Benefits of Physical Exercise

Engaging in physical activity is strongly associated with optimal physiological and psychological health (Perini et al., 2016). Children and young adults who engage in more physical exercise tend to display higher cognitive control and emotional regulation, perform better in school, and report higher general mood and lower levels of depressive affect than their more sedentary peers (Archer & Garcia, 2014). Neuroimaging studies demonstrate that individuals with higher levels of physical fitness have greater hippocampal volume (an area of the brain implicated in the formation of new memories), greater white matter integrity (neural structures critical for neural communication), and more efficient patterns of brain activity (Donnelly et al., 2016; Erickson et al., 2015). Habitual engagement in physical exercise also supports the production of proteins and neurotransmitters critical for brain cell survival and proliferation (Voelcker-Rehage et al., 2016).

Single, short bouts of physical exercise have also been shown to yield cognitive benefits; these include enhanced executive functioning in domains of attention, working memory, decision making, and cognitive flexibility (Pesce et al., 2009; Mahar, 2011). Despite the wealth of literature on the neurocognitive benefits of chronic physical exercise, the neural substrates underlying the more acute effects are less understood. Human and animal studies have demonstrated that short bouts of physical exercise rapidly alter aspects of neurochemistry, including increased monoamine and neurotropic factor release (promoting survival of neurons via growth, maturation, and maintenance of the cell), increased cerebral blood flow and increased hemoglobin oxygenation (supporting optimal neural functioning) (Giles et al., 2014; Zhou et al., 2006). A prominent hypothesis posits that physical exercise may increase levels of neurotransmitters, specifically dopamine, serotonin, and norepinephrine (Loprinzi et al., 2013). Dopamine is essential for motor and cognitive function, and norepinephrine is involved in the performance of executive functions, both leading to heightened cognitive performance and information processing (Ploughman, 2008; Ng et al., 2017). Another hypothesis suggests that physical exercise upregulates neurotrophins, such as brain-derived neurotrophic factor and blast growth factor, supporting neuronal survival and dendritic branching, necessary for cognitive performance (Zoladz et al., 2010). Most relevant to the current study, it has been proposed that short bouts of physical exercise increase PFC blood oxygenation (Yanagisawa et al., 2010). During demanding tasks, metabolic requirements of neurons require oxygen to sustain activity, making increased oxygenation necessary for optimal neuronal function (Tam, 2014). Though the exact mechanism remains unclear, ample evidence suggests that routine and even acute physical exercise leads to improved PFC function and executive functioning (Yanagisawa et al., 2010; Tsujii, Komatsu and Sakatani, 2012; Huang et al., 2014; Ludyga et al., 2017). These findings, in combination with executive functioning deficits and PFC dysfunction observed in ADHD, indicate that interventions involving physical exercise may be an efficacious avenue for improving PFC functioning and ultimately, executive functioning in children with ADHD.

1.7 Physical Exercise and Executive Functioning in ADHD Research

In populations with ADHD, engaging in long-term, routine physical exercise has been shown to result in significant improvements in various cognitive functions (Hoza, 2016). Verret and colleagues (2010) implemented a 10-week moderate-intensity physical exercise program for children with ADHD during lunch hour. Moderate-intensity physical exercise refers to a heart rate of 50-60% of maximum aerobic capacity, such as during biking on flat terrain, brisk walking, and swimming at a moderate pace. Researchers found that children in the physical exercise group demonstrated significant improvements on tasks of attention and response inhibition when compared to children in the "business as usual" group (i.e., they did not receive any intervention and participated in recess as usual). Similarly, Pan and colleagues (2016) implemented a 12-week table tennis after-school exercise program for children with ADHD and found significantly higher performance on measures of attention, cognitive flexibility, and inhibitory control compared to children with ADHD in the business as usual group (i.e., they were instructed to carry on with typical after school routines) and compared to typically developing controls following the intervention.

While routine physical exercise is an important aspect of a healthy lifestyle for any population, adherence to programs, implementation feasibility, and access to resources present challenges to this method as an intervention model for ADHD. Therefore, more recent focus has been directed towards investigating the potential benefits of how a single, short bout of physical exercise may have immediate positive effects on ADHD symptomology. Pontifex and colleagues

(2013) examined the effects of a single bout of moderate intensity aerobic physical activity on preadolescent children with ADHD using cognitive tasks, electroencephalogram (EEG) recording, and an academic performance assessment. Immediately following a single bout of physical activity, both children with ADHD and typically developing controls demonstrated increased response accuracy, stimulus reaction time, and reading and arithmetic performance. Those with ADHD also showed enhancements in regulatory processes when compared to children with ADHD in the control group, as well as increased P3 amplitude and decreased P3 latency during inhibition tasks, which suggests greater information processing efficiency. In a systematic review and meta-analysis of randomized control trials (Cerillo-Urbina et al., 2015), findings suggested that acute aerobic physical exercise had a moderate to large effect on attention, hyperactivity, and impulsivity, as well as related symptoms such as anxiety and social disorders in children with ADHD. Benzing, Chang, and Schmidt (2018) also showed that children with ADHD who engaged in a 15-minute bout of moderate intensity biking performed significantly faster than controls (who watched a documentary) on tasks requiring both inhibitory control and task switching, but not on tasks requiring working memory. Preliminary evidence suggests physical exercise in both acute and chronic forms is supported as an alternative intervention for ADHD. However, further research with rigorous trials are required to substantiate the effectiveness and efficacy of a short physical exercise session on executive functioning in children with ADHD.

1.8 Physical Exercise, the Prefrontal Cortex (PFC) and ADHD

It is still unclear how physical exercise aids in supporting PFC function and how this interaction supports executive functioning. Of the limited studies conducted, there is growing evidence that single bouts of physical exercise enhance PFC activity. In healthy populations, Yanagisawa and colleagues (2010) demonstrated that a short bout of moderate-intensity physical exercise enhanced PFC activity during tasks of executive functioning. Specifically, this enhancement of cortical activity coincided significantly with greater performance on tasks of executive functioning. Tsujii, Komatsu, and Sakatani (2012) found that an acute bout of moderate-intensity physical exercise improved accuracy on working memory tasks. This improvement also coincided with increased PFC activity, specifically within the left hemisphere.

Physical exercise has also been shown to enhance PFC activity in children with ADHD. Huang and colleagues (2014) found that children with ADHD who participated in an 8-week physical exercise program showed smaller theta/alpha ratios (which is positively associated with attention and memory) over the frontal area of the brain when compared to non-physical controls. Ludyga and colleagues (2017) found that after completion of a 20-minute moderate intensity biking condition, children with ADHD performed significantly better on a task of inhibition, with fewer mistakes and faster reaction time when compared to controls who watched a documentary on physical exercise. Additionally, EEG analysis showed that ADHD participants had increased P3 amplitude in the PFC while completing inhibition tasks (Ludyga et al., 2017), again suggesting increased processing efficiency of information.

Although there is considerable evidence that physical exercise positively impacts executive functioning, further research is needed to understand whether changes in PFC activity following a single bout of physical exercise constitutes, at least in part, a key underlying neural mechanism linking the effect of physical exercise on executive functioning in children with ADHD. Thus, this thesis aimed to further establish how physical exercise regulates PFC function in this group, and whether these changes in brain activity positively correlate with improved executive functioning. This information will provide further insight into the mechanisms underlying the link between physical exercise and cognition, as well as the feasibility of physical exercise as a potential therapeutic intervention for ADHD.

1.9 Physical Exercise and its Effect on Psycho-Emotional Aspects of ADHD

In addition to impairments in executive functioning, 80% of children and adults with ADHD have a co-occurring psychological disorder, particularly in the realm of affective and mood disorders such as anxiety and depression (Mayes et al., 2008). Affective and mood impairments for children with ADHD include poor emotional regulation, outbursts of anger and aggression, reduced empathy, and issues with effective coping strategies (Biederman et al., 2012). Unfortunately, one-third of children with ADHD are reported to have high levels of emotional difficulty associated with a distorted sense of self and suffer from low self-esteem (Gregory et al., 2012). Considering these associated symptoms, children with ADHD often struggle with social interaction, which is exacerbated by poor social and communication skills when compared to children without ADHD. Difficulty in understanding and establishing personal interaction often results in the lack of friendships and peer relationships, which further compound negative mood and depressive-like symptoms. Difficulties within social-emotional aspects of childhood can have detrimental effects on development, impact self-efficacy and motivation, and ultimately, their academic and social experiences in school (Frankel et al., 2002).

Self-efficacy and motivation are often used to predict academic achievement (Walker et al., 2006), and tend to be much lower in children with ADHD (Major et al., 2013; Volkow et al., 2011). Children who possess high self-efficacy believe they have the skills and capabilities to complete a task successfully and have the confidence to exert control over their own motivation, behaviour and environment (Bandura, 2010). These children are more likely to persist when faced with a challenge, seek out challenges, and are highly adaptable. Further, they are more likely to get higher grades and do better in school (Walker et al., 2006). Motivation is the process that stimulates the desire to initiate, guide, and maintain goals (Wigfield & Cambria, 2010). Children who are motivated enjoy the process of increasing their competency toward a specific task, are more likely to persist when faced with a challenging task, have a stronger self-concept, express more creativity, and also perform better in school (Gottfried et al., 2001). Unfortunately, stimulants, the first line of treatment for ADHD, can be ineffective in treating and often exacerbate lack of motivation and low self-efficacy, calling for additional effective treatment options (Cormier, 2008).

Engaging in physical exercise is related to improved affect, mood, emotional regulation, self-efficacy, and motivation, as well as decreased depressive and anxiety symptoms in all age groups (Peluso et al., 2005; Mata et al., 2012). Indeed, this link between physical exercise and improved psycho-emotional aspects is well established, only a few studies have examined this link among children and adolescents. A 10-year longitudinal study reported an inverse relationship between adolescent physical exercise participation, depression, and mood-related disorders (Birkeland et al., 2009). A systematic review by Cataldo and colleagues (2013) demonstrated a strong link between participation in physical exercise programs and improved self-efficacy in youth. We have also seen this effect in acute models of physical exercise. Hogan and colleagues (2013) found that 15 minutes of moderate intensity biking significantly improved affect in adult participants. In 9 and 10-year olds, Dinkie and colleagues (2001) found a significant increase in positive mood and a significant decrease in negative mood following 15-minutes of physical exercise. Additionally, Lee and colleagues (2016) found that a 30-minute bout of physical exercise significantly decreased ratings of negative mood in children. In recent years, researchers have begun to examine the link between physical exercise and improved affect and mood in ADHD populations. Fritz and colleagues (2016) found that a 20-minute bout of physical exercise improved motivation for cognitive tasks and general states of mood in young men with ADHD. Though this study shows promise, children and adolescent populations remain underexamined. Among the few studies looking at children and youth, Jensen and Kenny (2004) found that yoga led to decreased oppositional, restless, and impulsive behaviour in boys with ADHD 8-13 years old. Further, those who participated in yoga more often showed greater improvements in emotional stability. Kiluk, Weden, and Culotta (2009) found that participating in three or more sports yielded less severe anxiety and depression in children with ADHD. Verret and colleagues (2012) found a 10-week physical exercise program resulted in lower anxiety and depression scores, as well as fewer social problems among children in the treatment group. In summary, physical exercise positively impacts mood, affect, self-efficacy, and motivation in ADHD populations, but more research must be done to inform whether short bouts of physical exercise can also yield immediate positive benefits, especially among children and youth.

1.10 Current Thesis

The current thesis aimed to contribute to a greater understanding of how a single, short bout of physical exercise impacts executive functioning, PFC functioning, and psycho-emotional functioning in children with ADHD. In the current study, children with ADHD completed a battery of executive functioning tasks and psycho-emotional assessments before and after participating in a short 10min bout of moderate intensity biking. We used functional near infrared spectroscopy (fNIRS) to measure concentration changes in oxygenated and deoxygenated hemoglobin within their PFC during the executive functioning tasks (see Appendix A for a flow chart of the study procedure). Approximately 1 week later, they returned and completed the same experimental procedure but engaged in silent reading instead of physical exercise.

1.11 Hypotheses

There are three main hypotheses: 1) a single, short bout of physical exercise will improve performance on tasks of executive functioning, including inhibitory control, task switching and working memory, in children with ADHD; 2) a single, short bout of physical exercise will increase blood oxygenation in the PFC compared to silent reading. This increase in PFC oxygenation will be associated with improved performance on tasks measuring executive functioning; and 3) a single, short bout of physical exercise will improve self-efficacy, motivation, affect, and mood in children with ADHD.

Chapter 2: Methods

2.1. Participants

Based on prior research with a similar paradigm (Pontifex et al., 2013), 16 children with an ADHD diagnosis were recruited for this study. A sample size calculation was performed using G*Power with medium to large effect size Cohens d= 0.6-1, power of 0.95, alpha of 0.05, with primary outcome variable as change in EF, indicating 16-20 participants were needed. Our goal was to recruit 20 participants, but we were only able to recruit 16. The study took place from May 2019 to March 2020. Participants were recruited on a rolling basis through the Child and Youth Development Clinic at Western University as well as through Western's Mary J. Wright Research and Education Centre at Merrymount. Participants were aged 10-14 (M = 11.38; SD = 1.5) and there were 5 females and 11 males. Exclusion criteria included non-English speakers, children who were not fully literate, those who had any neurological or developmental exceptionalities outside of ADHD, and those who were colour-blind. The method section will describe the cognitive assessments and neuroimaging techniques used, the demographic and ADHD diagnostic information that were collected, as well as the full study procedure.

2.2 Cognitive Assessments

2.2.1 Stroop Test (Stroop, 1935).

The Stroop Test is a non-invasive and reliable measure of inhibitory control and is often used to assess executive functioning in children with ADHD (Goldberg et al., 2005; Scarpina & Tagini, 2017). There are two versions of the Stroop test, congruent and incongruent. The congruent trial requires participants to read a list of colours for 30 seconds. Each word is printed in the colour that it is listed. Blue, for example, would be printed in the colour blue (see Appendix B). The incongruent trial requires participants to read aloud a list of colours for 150 seconds, but the words are printed in a colour different than the word itself. For example, the word 'red' would be printed in the colour purple, and participants would be required to say 'purple' rather than the actual word 'red' (See Appendix C). Participants had to go as quickly as possible through the list of words without making errors. The number of words read, and the number of errors produced were recorded and used as outcome measures.

2.2.2 Trail Making Test (TMT) (Reitan, 1955).

The TMT is made up of two parts and is a reliable and valid measure of EF in children (Reitan, 1955). The first part, TMT-A (Appendix D), is a measure of attention, while the second part, TMT-B (Appendix E), is a measure of cognitive flexibility and task switching (Reitan, 1955; Rosin & Levett, 1989). TMT-A requires the participant to draw one sequential line to connect 25 encircled numbers that are randomly distributed across a piece of paper. The TMT-B is similar, but requires the participant to alternate between connecting numbers and letters (e.g., 1, A, 2, B, 3, C, etc.) The amount of time the participant takes to complete the task (as recorded by a stopwatch), and the number of errors made were used as outcome measures.

2.2.3 Working Memory Task

Participants' working memory was assessed by the reverse memory (RM) subscale of the Leiter-3 International Performance Scale, a valid and reliable indicator of working memory

(Roid et al., 2013). The RM subscale is a complex task that requires the participant to mentally store and manipulate information (See Appendix F). The task involved a series of pictures laid out in front of the participant. The experimenter pointed to various pictures in a sequence, and the participant then had to point to the pictures in reverse order of what was presented. The number of pictures that needed to be recalled in reverse order increased from 2-9; after six errors were produced, the final number of pictures that were correctly recalled were recorded as the participants' working memory span.

2.3 Psycho-emotional Outcomes

2.3.1 Motivation

Participants' motivation to complete the cognitive battery was assessed via the Effort and Importance subscale from the Intrinsic Motivation Inventory by McAuley, Duncan & Tammen (1989). This questionnaire asked participants 5 questions regarding their effort, energy, and personal importance towards doing well on the cognitive tasks. This was collected prior to and following the cognitive tasks (see Appendix G).

2.3.2 Affect

Affect was assessed using the Feeling Scale (FS) by Hardy & Rejeski (1989). This questionnaire uses a scale from -5 (very bad) to +5 (very good) to measure how participants were feeling before and after cognitive tasks (see Appendix H).

2.3.3 General Self-Efficacy

General Self-Efficacy was measured by the "General Self-Efficacy" scale developed by Chen, Gully, and Eden (2001). This measures how confident one is to perform successfully on tasks and situations. The scale ranges from 1 (strongly disagree) to 5 (strongly agree), asking participants 8 questions on their confidence in achieving goals and accomplishing tasks that are presented to them (see Appendix I). Participants' completed the scale at the beginning and at the end of the experimental protocol.

2.3.4 Mood (POMS)

Mood was assessed via the "Adapted Version of the Profile of Mood States" by Williamson and colleagues (2001). This questionnaire assesses a variety of feelings from Active and Happy to Tired and Unhappy. Participants were required to rate their current state of the 11 different feelings on a scale of 1 (not at all) to 10 (extremely). Five items reflected positive mood states, and five items reflected negative mood states (See Appendix J). Participants' completed the scale at the beginning and at the end of the experimental protocol.

2.4 Equipment

2.4.1 fNIRS Neuroimaging Device.

A multichannel continuous wave fNIRS device (NIRScout; NIRx Medical Technologies, Brooklyn, NY) was used to measure hemodynamic physiological responses. Data from the PFC (region of interest) and the motor cortex (control region) were obtained. The motor cortex was used as a control region so that any changes in PFC hemoglobin levels could be attributed to the PFC in particular, not to overall hemoglobin deviations. The montage used consisted of sixteen dual-wavelength sources (760 and 850 nm) and sixteen detectors separated by 3cm, the optimal distance for balancing depth sensitivity with the signal to noise ratio (Strangman et al., 2013)

fNIRS measures changes in hemoglobin concentrations in the blood, a molecule that carries oxygen in the brain, which can be used as an indirect measure of brain activity (Thomas et al., 2012). Oxygenated hemoglobin (oxy-Hb) reflects the inflow of oxygen into neural tissue, whereas deoxygenated hemoglobin (deoxy-Hb) reflects the amount of oxygen that is absorbed by the tissue. In homeostasis, both the inflow of oxy-Hb and the formation of deoxy-Hb should be constant, as the amount of oxygen being consumed by the tissue is equal to the amount of oxygen being carried towards the tissue. During activation of the tissue (e.g., excitation of brain areas), oxygen is consumed within the tissue, and hemodynamically, the tissue responds by increasing the flow of blood toward that tissue (referred to as neurovascular coupling; Thomas et al., 2012). Representing both oxy-Hb and deoxy-Hb provides the most information about changes in blood volume in the tissue underneath the sensors.

During fNIRS data collection, infrared emitting optodes sit on the surface of the scalp and pass light through the skin and skull, which is then absorbed by the underlying neural tissue at varying concentrations (depending on the amount of blood within a region). When the light reaches the detectors, the amount of light that was absorbed by the underlying neural tissue is used to calculate changes in oxygenated and deoxygenated hemoglobin concentration. Optical data were collected by the detectors at a sampling rate of 62.5 Hz and was converted into a measure of hemoglobin signal using the Beer-Lambert Law (Cope & Delpy, 1991).

The source and detector optodes are embedded into a soft, snug cap that is placed on a participant's head (see Appendix K for equipment schematics). Because it is comfortable to wear, fNIRS is generally accepted by participants (Thomas et al., 2012). fNIRS is also less restrictive, expensive, and sensitive to motion artifacts compared to other imaging techniques (e.g., fMRI; Thomas et al., 2012). Accordingly, fNIRS is considered a valuable and safe imaging technique with clinical populations, including those with ADHD (Ferrari & Quaresima, 2004; Maddalen et al., 2018).

2.4.2 fNIRS Data Preprocessing.

The NIRx open-source nirsLAB software package (https://nirx.net/nirslab-1) was used to process the fNIRS data. The modified Beer-Lambert Law was used to convert optical density data into hemoglobin signals in millimole units. Raw data were bandpass filtered with a consistent high cut-off frequency of 0.01 Hz, and a variable low cut-off frequency ranging between 0.00038 HZ - 0.0007 HZ depending on how long each participant took to complete the experimental session. The bandpass filter was used to remove baseline drift and some physiological noise (e.g., heart rate). Both oxygenated hemoglobin (oxy-Hb) and deoxygenated hemoglobin (deoxy-Hb) were used in analyses.

2.4.3 fNIRS Channel Exclusion

A total of 55 channels comprised the PFC and motor montage. Channels 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 35, 43, and 54 corresponded to the PFC region; channels 29, 30, 31, 32, 33, 34, 36, 37, 38, 39, 40, 41, 42, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, and 55 corresponded to the motor region. Each channel was evaluated for signal quality using the coefficient of variation (CV) method. The CV value was set to 15, which is commonly used in other fNIRS studies (e.g., Kenville et al., 2017; Piper et al., 2014), and any channel that exceeded that value was removed from further fNIRS processing. All data were then exported into an excel macro that was designed to selectively average the oxy-Hb and deoxy-Hb concentration during the different cognitive tasks.

2.4.4 Biking Condition

The biking condition required the participant to peddle at a moderate intensity for 10 minutes on a stationary age-appropriate exercise bike. Though there are various forms of and intensity levels of physical exercise, aerobic physical exercise at moderate levels of intensity appears to consistently benefit cognitive function within the literature (Pontifex, 2019; Chang and Etnier, 2009). Cycling modalities are currently the most studied, and most effective form of physical exercise when looking at improvements in cognition (Pontifex et al., 2019). Following the cognitive tests, participants were asked to apply a Fitbit heart rate monitor to their wrist to assure appropriate exertion during biking. Participants were instructed to stay at moderate intensity, as determined by 65-85% of the maximum heart rate for their age (Kamijo, Khan, and Pontifex, 2012). Participants were instructed to attempt to stay within their target heart rate zone, which for a 10-year old would be between 105-126 bpm. If participants' heart rates were lower than a moderate level for their age, they would be instructed to peddle faster. If they had a higher heart rate than required, they would be instructed to slow down their peddling.

2.4.5 Silent Reading

The Silent Reading task required that the participant sit down and read their choice of an age-appropriate magazine that was provided by the lab for 10 minutes.

2.5 Design

The study used a within-subjects design where each participant partook in both study conditions. The study consisted of 3 sessions separated by 1 week: Day 1= Familiarization session; Day 2= Physical Exercise condition; Day 3= Control condition. Day 2 and 3 were counterbalanced across participants.

2.6 Procedure

2.6.1 Day 1: Familiarization and Questionnaires.

Participants, along with their parents, visited the lab within the Western Interdisciplinary Research Building for approximately 45 minutes to become familiar with the study procedure. Children and parents learned about the study's protocol and what they could expect during each visit. Parents were provided with a Letter of Information and Consent form and had contents orally described. Children were provided with a Letter of Information and Assent form, which was also orally described. Following obtained consent, one researcher escorted the child to an adjacent room and began to familiarize the participant with the cognitive tasks (in order to avoid poor performance on the first day due to novelty), and also began to familiarize the participant with the fNIRS system and the 10-minute biking protocol. Another researcher sat down with the parent(s) and assisted them in completing two assessments to verify their child's ADHD status, as well as gather demographic and medication information about their child.

2.6.2 Parents Protocol

Parents completed the Vanderbilt Parent Rating Scale (VADPRS) as well as the Behavior Rating Inventory of Executive Functioning (BREIF). The VADPRS included all 18 of the DSM criteria for ADHD, as well as eight criteria for oppositional defiant disorder and 12 criteria for conduct disorder (Wolraich et al., 2003). The tool requires parents to rate the severity of several behaviours on a 4-point scale, ranging from 'never' to 'very often'. An ADHD diagnosis is considered present if scores indicate that a behavior is either present 'often' or 'very often'. The BRIEF was also used to assess ADHD and verify the participants' ADHD diagnosis. The BRIEF is an 86-item questionnaire designed to measure eight different aspects of EF, including inhibition, shifting, emotional control, initiation, working memory, planning and organization, order and organization, and monitoring. The results from the VADPRS and the BRIEF were not used for analysis purposes, but rather to offer a thorough description of the participants' ADHD diagnosis (See Table 7) Finally, parents completed a Demographics and Medication Questionnaire to provide additional information about their children, such as age, sex, socioeconomic status, medication use, and history (See Table 6).

2.6.3 Child Protocol

Meanwhile, another researcher had the child perform baseline measurements and gathered further information. Children completed the Child Physical Activity Questionnaire (CPAQ). This is a 7-day recall instrument used to assess general physical exercise levels throughout the week. The questionnaire consists of answering questions such as "do you play soccer? If yes, how many hours per week?'. These results were not used for analysis purposes, but rather to offer a thorough description of the participants' physical exercise involvement, which is included in the demographics table (See Appendix L) Participants were then asked to remove their shoes and to step onto a floor scale to measure weight, stand against a vertically displayed measuring tape to determine height, as well as perform a standing long jump, which involved jumping from one stationary upright position as far forward as possible, landing in a stationary upright position, measuring explosive leg power (Ruiz et al., 2011). Participants were then asked to squeeze a handgrip dynamometer to measure their grip strength (Norman et al., 2011), which is an index of musculoskeletal health. (Ruiz et al., 2011). After these tasks were performed, the researcher allowed the child to become familiar with the cognitive battery by leading them through the Stroop Test, Trail Making Test, and the Leiter 3, which were then performed on days 2 and 3 of the study. The participants also became familiar with the fNIRS neuroimaging equipment. Specifically, the researcher used a fabric measuring tape to measure the circumference of the participants head, which determined the appropriately sized cap to be used on testing days. Children tried on the correct cap, touched the infrared optodes to become comfortable with them, and to assure them they were harmless. They also had the opportunity to see what their brain activity looked like on a display screen. Participants then became familiar with the biking protocol and biked for 10 minutes to enssure they felt comfortable and were capable of completing the study.

2.7 Biking Day.

Participants returned one week after their familiarization day and were asked to participate in a 10-minute moderate-intensity biking protocol. Participants were then reintroduced to the fNIRS system, which was then gently placed on their head for one minute to obtain baseline neural activation data. Next, with the cap still on, participants were administered the mood, self-efficacy, affect, and motivation questionnaires. Following the completion of the psycho-emotional measures, fNIRS data collection began, and participants completed the Congruent Stroop, the Incongruent Stroop, Trail Making task A and B, and the Leiter-3 International Performance Scale Reverse Memory subtest to obtain baseline executive functioning. After completion of the cognitive tasks, the participant was instructed to sit on the bike and to begin pedaling. Every 1 minute, researchers checked and recorded participants' heart rate. The average heart rate across participants was 117.5bmp, which is slightly below 60% of the maximum heart rate for 10-14yr old's. If they were below the designated level, they were encouraged to peddle quicker. If they were too far above, they were encouraged to peddle slower. Additionally, every 1 minute, researches asked participants to rate their perceived exertion (0= not working hard at all…5= strongly working…10= extremely strongly). This information was collected to monitor that the participant was not overworking or not working hard enough. The average perceived exertion was 7.1, which indicates a self-reported moderate intensity physical exercise range (See Appendix K). Following the 10 minutes of moderate intensity biking, researchers reapplied the fNIRS cap, re-administered the psycho-emotional questionnaires, and then the cognitive battery. These immediate tests are referred to as time 1 (T1). Participants were then given a children's magazine to quietly read for 10 minutes. Following this wait period, researchers reapplied the fNIRS cap, re-administered the psycho-emotional questionnaires, and then the cognitive battery again, serving as their scores for time 2 (T2). Two time points were analyzed to assess the immediate impact of the intervention as well as after a slight delay. The fNIRS system was then removed, and children were thanked and returned to their parents.

2.8 Control session.

The same protocol as Day 2 was followed, with participants being asked to read child-appropriate magazines instead of the 10 minutes of biking.

Chapter 3: Results

3.1 Research Question 1: Does a single, short bout of physical exercise improve performance on tasks of executive functioning in children with ADHD?

To answer this research question, we conducted several repeated measures ANOVAs with a two-level factor of *condition* (Physical Exercise vs. Control), and a three-level factor of *time* (pre-intervention, immediately post-intervention, and 10mins post-intervention). For inhibitory control, repeated measures ANOVAs were conducted for congruent and incongruent trials of the Stroop task; outcome variables were comprised of the number of words read and proportion correct. For sustained attention/task switching, repeated measures ANOVAs were conducted for Trail Making A and B tasks separately; outcome variables were comprised of time to completion (seconds) and number of errors. For working memory, a repeated measures ANOVA was conducted with the outcome variable comprised of the number of maximum items held in working memory. Age and sex were included as covariates in analyses if they were significant predictors of outcomes. There were no extreme outliers consistent across outcome variables and conditions. There were also no differences in performance regardless of whether participants first participated in the physical exercise condition or the control condition (all *p*s>.05). Greenhouse-Geisser was reported if Mauchly's Test of Sphericity indicated that the assumptions of sphericity had been violated.

3.1.2 Inhibitory Control

For congruent Stroop task performance, with *number of words read* as the outcome variable, there was no main effect of condition F(1, 15) = 0.074, $p = .790$, $\eta p^2 = 0.005$, (Physical exercise; M=57.81, SD=12.450; Control; M=57.15, SD=13.251), a significant main effect of time F(2, 30) = 4.493, $p = .020$, $\eta p^2 = 0.231$, with number of words read declining across time in both conditions, and no interaction F(1.424, 21.361) = 0.361, $p = .630$, $\eta p^2 = 0.024$. Age and sex were not included as covariates as they were not predictors of outcome (all Fs < 3.912, all *p*s > .070). There were no baseline differences in the number of words read for congruent Stroop between Physical Exercise and Control $t(15) = -0.351$, $p = .731$.

With *proportion correct* as the outcome variable, there was no main effect of condition F(1, 15) = 2.945, $p = .107$, $\eta p^2 = 0.164$ (PA; M=.99, SD=.010; Control; M=.99, SD=.025), no main effect of time F(1.357, 20.354) = 1.699, $p = .210$, $\eta p^2 = 0.102$, and no interaction F(1.482, 22.224) = 1.065, $p = .342$, $\eta p^2 = 0.066$. Age and sex were not included as covariates as they were not predictors of outcome (all Fs < 1.118, all *p*s > .310). There was no baseline difference in congruent Stroop 'proportion correct' between Physical Exercise and Control $t(15) = 0.954$, $p = .355$.

For incongruent Stroop task performance, with *number of words read* as the outcome variable, there was a main effect of condition F(1, 15) = 5.878, $p = .028$, $\eta p^2 = 0.282$ (Physical

Exercise; M=114.40, SD=29.776; Control; M=106.15, SD=29.106), no main effect of time F(2, 30) = 1.285, *p* = .291, ηp_2 = 0.079, and no interaction F(2, 30) = 1.351, *p* = .274, ηp_2 = 0.083. Age and sex were not included as covariates as they were not predictors of outcome (all Fs < 4.226, all *p*s > .060). There was no baseline difference in congruent Stroop words read between Physical Exercise and Control *t*(15) = 1.278, *p* = .22.

For incongruent Stroop task performance, with *proportion correct* as the outcome variable, there was no main effect of condition F(1,15) = 895, *p* = .359, ηp_2 = .056 (Physical Exercise; M=.96, SD=.024; Control; M=.95, SD=.035), no main effect of time F(2, 30) = .472, p = .628, ηp_2 = 0.031 and no interaction F(2, 30) = 2.490, *p* = .100, ηp_2 = .142. Age and sex were not included as covariates as they were not predictors of outcome (all Fs < .697, all *p*s > .419). There was no baseline difference in proportion correct for congruent Stroop between Physical Exercise and Control *t*(15) = .658, *p* = .521.

3.1.3 Sustained Attention/Tasking Switching

For Trail Making A, with *time to completion* as the outcome variable there was no main effect of condition F(1, 14) = 1.564, *p* = .232, ηp_2 = 0.101 (Physical Exercise; M=49.93, SD=22.185; Control; M=61.11, SD=26.984), no main effect of time F(2, 28) = .329, *p* = .723, ηp_2 = 0.023, and no interaction F(2, 28) = 1.58, *p* = .855, ηp_2 = 0.011. Sex was not included as a covariate as it was not a predictor of outcome (F = 0.34, *p* = .856). Age was included as a covariate as it was a predictor of outcome (F = 4.747, *p* = 0.48). There was no baseline difference in *time to completion* in Trail Making A between Physical Exercise and Control *t*(15) = -1.844, *p* = .085)

For Trail Making A, with *number of errors* as the outcome variable there was no main effect of condition F(1, 15) = .319, *p* = .580, ηp_2 = 0.021 (Physical Exercise; M=.14, SD=.367;

Control; M=.10, SD=.348), no main effect of time F(1.206, 18.088) = 2.647, $p = .116$, ηp_2 = 0.150, and no interaction F(2, 30) = 2.54, $p = .777$, $\eta p_2 = 0.017$. Sex and age were not included as covariates as they were not predictors of outcome (all Fs < 2.462, all *ps* > .141). There was no baseline difference in *number of errors* in Trail Making A between Physical Exercise and Control $t(15) = .620$, $p = .544$).

For Trail Making B, with *time to completion* as the outcome variable there was no main effect of condition F(1, 15) = 1.26, $p = .727$, $\eta p_2 = 0.008$ (Physical Exercise; M=97.75, SD= 43.466; Control; M=100.81, SD = 34.45), no main effect of time F(1.276, 19.138) = 0.74, p = .847, $\eta p_2 = 0.005$, and no main effect of interaction F(1.386, 20.795) = 0.689, $p = .462$, ηp_2 = 0.044. Age and sex were not included as covariates as they were not predictors of outcome (all Fs < .807, all *p*s > .385). There were no baseline differences in time to completion in Trail Making B between Physical Exercise and Control $t(15) = -.181$, $p = .859$).

For Trail Making B, with *number of errors* as the outcome variable there was no main effect of condition F(1, 15) = 1.705, $p = .211$, $\eta p_2 = 0.102$ (Physical Exercise; M= 1.04, SD=1.646; Control; M=.69, SD=1.134), no main effect of time F(2, 30) = 0.76, $p = .927$, ηp_2 = 0.005, and no interaction F(2, 30) = .333, $p = .719$, $\eta p_2 = 0.022$. Sex and age were not included as covariates as they were not predictors of outcome (all Fs < 1.626, all *ps* > .430). There was no baseline difference in *number of errors* in Trail Making B between Physical Exercise and Control $t(15) = 1.291$, $p = .216$)

3.1.4 Working Memory

For Leiter-3, with working memory span as the outcome variable there was no main effect of condition F(1, 15) = .044, $p = .836$, $\eta p_2 = 0.003$ (Physical Exercise; M=15.56, SD=2.707; Control; M=15.65, SD=2.137), no main effect of time F(2, 30) = 1.549, $p = .229$,

$\eta p_2 = 0.094$, and no interaction $F(1.452, 21.773) = .739$, $p = .448$, $\eta p_2 = 0.047$. Sex and age were not included as covariates as they were not predictors of outcome (all $Fs < 2.784$, all $ps > .119$). There was no baseline difference in working memory span between PA and Control $t(15) = -.696$, $p = .497$.

3.2 Research Question 2: How will a single PA bout impact the PFC and what is the corresponding impact on executive functioning?

fNIRS outcome variables consisted of change scores in oxygenated and deoxygenated hemoglobin from post-intervention T1 to pre-intervention, and from post-intervention T2 to pre-intervention. Only fNIRS data that corresponded to significant executive functioning outcomes were analyzed (i.e., Incongruent Stroop). We conducted repeated measures ANOVAs with a two-level factor of condition (PA vs. Control) and a two-level factor of time (change scores from post-intervention T1 – pre-intervention; change scores from post-intervention T2 – pre-intervention); this was done for PFC and motor regions separately. Age and sex were included as covariates in analyses if they were significant predictors of outcomes. There were no extreme outliers consistent across outcome variables and conditions. There were also no differences in PFC hemoglobin concentration regardless whether participants first participated in the Physical Exercise condition or the control condition (all $ps > .05$). Greenhouse-Geisser was reported if Mauchly's Test of Sphericity indicated that the assumptions of sphericity had been violated.

3.2.1 Incongruent Stroop

For the PFC, with oxygenated hemoglobin change scores as the outcome variable, there was no main effect of condition $F(1, 14) = .327$, $p = .577$, $\eta p_2 = 0.023$ (Physical Exercise; M=0.1, SD=.39; Control; M=.05, SD=.405), no significant main effect of time $F(1, 14) = 1.824$, $p = .198$, $\eta p_2 = 0.115$, and no interaction $F(1, 14) = .005$, $p = .947$, $\eta p_2 = 0.000$. There was no baseline difference in oxygenated hemoglobin changes in the PFC between Physical Exercise and Control $t(14) = -.382$, $p = .708$. For the PFC, with deoxygenated hemoglobin change scores as the outcome variable, there was no main effect of condition $F(1, 14) = 1.310$, $p = .272$, $\eta_p^2 = 0.086$ (Physical Exercise; M=.05, SD=.48; Control; M=-.05, SD=.335), no significant main effect of time $F(1, 14) = .136$, $p = .718$, $\eta_p^2 = 0.010$, and no interaction $F(1, 14) = .718$, $p = .411$, $\eta_p^2 = 0.049$. Age and sex were not included as covariates as they were not predictors of outcome (all Fs < 1.070, all *p*s > .321). There was no baseline difference in deoxygenated hemoglobin changes in the PFC between Physical Exercise and Control $t(14) = -1.456$, $p = .168$.

For the motor region, with oxygenated hemoglobin change scores as the outcome variable, there was no main effect of condition $F(1, 14) = .004$, $p = .953$, $\eta_p^2 = 0.000$ (Physical Exercise; M=.2, SD=.7; Control; M=.25, SD=1.03), no significant main effect of time $F(1, 14) = 1.519$, $p = .238$, $\eta_p^2 = 0.098$, and no interaction $F(1, 14) = 1.557$, $p = .080$, $\eta_p^2 = 0.203$. There was no baseline difference in oxygenated hemoglobin changes in the motor region between Physical Exercise and Control $t(14) = -.151$, $p = .882$. For the motor region, with deoxygenated hemoglobin change scores as the outcome variable, there was no main effect of condition $F(1, 14) = .181$, $p = .677$, $\eta_p^2 = 0.013$ (Physical Exercise; M=.05, SD= .55; Control; M=.1, SD=.555), and no main effect of time $F(1, 14) = .139$, $p = .715$, $\eta_p^2 = 0.010$. There was a significant interaction $F(1, 14) = 6.601$, $p = .022$, $\eta_p^2 = 0.320$. Age and sex were not included as covariates as they were not predictors of outcome (all Fs < .854, all *p*s > .459). There was no baseline difference in deoxygenated hemoglobin changes in the motor region between Physical Exercise and Control $t(14) = -1.854$, $p = .085$.

Bivariate correlations were also conducted between fNIRS outcomes and the corresponding significant executive function. This was done to address the research question aimed at understanding whether significant changes in neural activity were correlated with significant changes in executive functioning. No correlations were found between PFC oxygenated, deoxygenated and Incongruent Stroop with 'number completed' as the outcome variable (all *r*s < .566; all *p*s > .069).

3.3 Research Question 3: Does a single, short bout of physical exercise improve mood, self-efficacy, motivation and affect in children with ADHD?

To assess this research question, we conducted paired samples t-tests to assess changes in mood and general self-efficacy from pre-intervention to post-intervention within each condition. To assess the effect of Physical Exercise on motivation and affect, we conducted several repeated measures ANOVAs with a two-level factor of condition (Physical Exercise vs. Control), and a three-level factor of time (prior/post first cognitive battery, prior/post second cognitive battery, and prior/post third cognitive battery). There were no extreme outliers consistent across outcome variables and conditions. There were also no differences in psycho-emotional outcomes regardless of whether participants first participated in the physical exercise condition or the control condition (all *p*s>.05). Greenhouse-Geisser was reported if Mauchly's Test of Sphericity indicated that the assumptions of sphericity had been violated.

3.3.1 Mood

In the Physical Exercise condition, with positive mood as the outcome variable, there was a significant increase in positive mood from the beginning of the experiment (M=3.615, SD=.823) to the end of the experiment (M= 6.74, SD=1.629), $t(15) = -2.70$, $p = .016$. In the Control condition, there was no significant change in positive mood from beginning (M=3.63, SD=.986) to the end of the experiment (M= 3.739, SD=.841), t(15) = -1.028, p = .320. There was no baseline difference in positive mood between Physical Exercise and Control $t(15) = -.072$, p = .943.

3.3.2 Negative Mood

In the Physical Exercise condition, with negative mood as the outcome variable, there was no change in negative mood from the beginning (M=1.625, SD=.4435) to the end of the experiment (M= 1.588, SD= .549), $t(15) = .305$, p= .764. In the Control condition, there was also no change in negative mood from the beginning (M=1.54, SD=.454) to the end (M= 1.54, SD=.454) of the experiment, $t(15) =.169$, p= .868. There was no baseline difference in negative mood between Physical Exercise and Control $t(15) = .778$, p = .449.

3.3.2 General Self Efficacy

In the Physical Exercise condition, with general self-efficacy as the outcome variable, there was a significant increase in general self-efficacy from the beginning (M=3.652, SD=.772) to the end of the experiment (M= 3.82, SD= .743), $t(15) =-2.294$, p= .037. In the Control condition, there was no change in general self-efficacy from the beginning (M=3.82, SD=.813) to the end of the experiment (M= 3.91, SD=.869), $t(15) =-1.112$, p= .284. There was no baseline difference in general self-efficacy between Physical Exercise and Control $t(15) = -1.292$, p = .216.

3.3.3 Affect Before Cognitive Tasks

With affect *before the cognitive tasks* as the outcome variable there was no main effect of condition $F(1, 15) = 2.740$, $p = .119$, $\eta p_2 = 0.154$ (Physical Exercise; M=3.31, SD=1.976; Control; M=3.87, SD=1.355), no main effect of time $F(2, 30) = 2.143$, $p = .135$, $\eta p_2 = 0.125$, and no interaction $F(1.478, 22.173) = 0.495$, $p = .561$, $\eta p_2 = 0.032$. Age and sex were not included as covariates as they were not predictors of outcome (all Fs < .483, all *p*s > .845). There was no baseline difference in affect between Physical Exercise and Control $t(15) = -1.952$, $p = .70$.

3.3.4 Affect After the Cognitive Tasks

With affect *after the cognitive tasks* as the outcome variable there was a marginal main effect of condition $F(1, 15) = 4.483$, $p = .051$, $\eta p_2 = 0.230$ (Physical Exercise; M=3.35, SD=1.702; Control; M=4.06, SD=1.090) with the Physical Exercise condition promoting higher overall affect, a main effect of time $F(2, 30) = 4.171$, $p = .025$, $\eta p_2 = 0.218$, and no interaction $F(1.365, 20.474) = 0.248$, $p = .697$, $\eta p_2 = 016$. Age and sex were not included as covariates as they were not predictors of outcome (all Fs < .483, all *p*s > .499). There was no baseline difference in affect between Physical Exercise and Control $t(15) = -1.952$, $p = .70$.

3.3.5 Motivation Before the Cognitive Tasks

With motivation *before the cognitive tasks* as the outcome variable there was no main effect of condition $F(1, 15) = .088$, $p = .771$, $\eta p_2 = 0.006$ (Physical Exercise; M=5.84, SD=1.178; Control; M=5.79, SD=1.106), there was a main effect of time $F(2, 30) = 4.323$, $p = .024$, $\eta p_2 = 0.220$ with motivation generally increasing across time, and there was no interaction $F(1.445, 21.677) = 0.073$, $p = .873$, $\eta p_2 = .005$. Age and sex were not included as covariates as they were not predictors of outcome (all Fs < .486, all *p*s > .808). There was no baseline difference in motivation *before the cognitive tasks* between Physical Exercise and Control $t(15) = 0.094$, $p = .927$.

3.3.6 Motivation After the Cognitive Tasks

With motivation *after the cognitive tasks* as the outcome variable there was no main effect of condition $F(1, 15) = .001$, $p = .975$, $\eta p_2 = .000$ (Physical Exercise; M=5.92, SD=1.177; Control; M=5.92, SD=1.098), no main effect of time $F(1.390, 20.857) = 3.574$, $p = .061$, $\eta p_2 =$

0.192, and no interaction $F(2, 30) = .448$, $p = .643$, $\eta_p^2 = .029$. Age and sex were not included as covariates as they were not predictors of outcome (all Fs < .693, all *p*s > .788). There was no baseline difference in motivation *after the cognitive tasks* between Physical Exercise and Control $t(15) = 0.094$, $p = .927$.

Table 1
Descriptive Statistics for Cognitive Tasks

	Physical Exercise M *(SD)*	**Control M *(SD)***	**N**
Congruent Stroop # Complete – Pre	59.50 (*11.17*)	60.44 (*12.38*)	16
Congruent Stroop # Complete – Post 1	58.56 (*12.83*)	57.88 (*11.20*)	16
Congruent Stroop # Complete – Post 2	55.37 (*13.35*)	53.13 (*16.16*)	16
Congruent Stroop Proportion Correct -Pre	1.00 (*.01*)	.99 (*.02*)	16
Congruent Stroop Proportion Correct -Post 1	1.00 (*.01*)	1.00 (*.01*)	16
Congruent Stroop Proportion Correct -Post 2	.99 (*.01*)	1.00 (*.04*)	16
Incongruent Stroop # Complete -Pre	115.19 (*31.23*)	109.13 (*28.76*)	16
Incongruent Stroop # Complete -Post 1	116.12 (*31.71*)	103.13 (*28.76*)	16
Incongruent Stroop # Complete -Post 2	111.88 (*26.37*)	105.69 (*29.09*)	16
Incongruent Stroop Proportion Correct -Pre	.96 (*.02*)	.96 (*.04*)	16
Incongruent Stroop Proportion Correct -Post 1	.96 (*.02*)	.95 (*.04*)	16
Incongruent Stroop Proportion Correct -Post 2	.95 (*.02*)	.96 (*.04*)	16
Trail Making A Time to Completion - Pre	50.26 (*24.37*)	63.27 (*28.06*)	16
Trail Making A Time to Completion – Post 1	51.24 (*19.50*)	53.63 (*23.76*)	16
Trail Making A Time to Completion – Post 2	48.29 (*22.69*)	66.43 (*29.12*)	16
Trail Making A Number of Errors - Pre	.31 (*.60*)	.19 (*.54*)	16
Trail Making A Number of Errors – Post 1	.06 (*.25*)	.06 (*.25*)	16
Trail Making A Number of Errors – Post 2	.06 (*.25*)	.06 (*.25*)	16
Trail Making B Time to Completion - Pre	99.28 (*45.53*)	101.35 (*33.66*)	16
Trail Making B Time to Completion – Post 1	101.64 (*47.82*)	97.21 (*31.05*)	16
Trail Making B Time to Completion – Post 2	92.33 (*37.04*)	103.87 (*38.65*)	16

Trail Making B Number of Errors - Pre	1.13 (*1.31*)	.63 (*.89*)	16
Trail Making B Number of Errors – Post 1	1.19 (*1.87*)	.69 (*1.08*)	16
Trail Making B Number of Errors – Post 2	.81 (*1.76*)	.75 (*1.44*)	16
Leiter 3 Number Complete - Pre	15.06 (*3.47*)	15.69 (*1.78*)	16
Leiter 3 Number Complete – Post 1	15.69 (*2.70*)	15.25 (*2.27*)	16
Leiter 3 Number Complete – Post 2	15.94 (*1.95*)	16.00 (*2.37*)	16

Table 2
Descriptive Statistics fNIRS

	Physical Exercise M (*SD*)	**Control M (*SD*)**	***N***
PFC Oxygenated Hemoglobin Post 1	.20 (*.39*)	.10 (*.44*)	15
PFC Oxygenated Hemoglobin Post 2	.08 (*.39*)	.01 (*.37*)	15
PFC Deoxygenated Hemoglobin Post 1	.007 (*.24*)	.10 (*.26*)	15
PFC Deoxygenated Hemoglobin Post 2	.002 (*.72*)	.005 (*.41*)	15
Motor Oxygenated Hemoglobin Post 1	.30 (*.62*)	.002 (*.65*)	15
Motor Oxygenated Hemoglobin Post 2	.14 (*.78)*	.50 (*1.14*)	15
Motor Deoxygenated Hemoglobin Post 1	-.10 (*.35*)	.20 (*.55*)	15
Motor Deoxygenated Hemoglobin Post 2	.20 (*.75*)	.03 (*.56*)	15

Table 3

Descriptive Statistics for Mood and General Self Efficacy

	Physical Exercise M (*SD*)	**Control M (*SD*)**	**N**
Ratings of Positive Mood - Pre	3.61 (*.82*)	3.63 (*.99*)	16
Ratings of Positive Mood – Post 2	3.91 (*.87*)	3.74 (*.84*)	16
Ratings of Negative Mood - Pre	1.63 (*.44*)	1.55 (*.48*)	16
Ratings of Negative Mood – Post 2	1.59 (*.55*)	1.54 (*.45*)	16
Ratings of General Self-Efficacy - Pre	3.65 (*.77*)	3.82 (*8.13*)	16
Ratings of General Self-Efficacy – Post 2	3.82 (*.74*)	3.91 (*.87*)	16

Table 4
Descriptive Statistics for Motivation and Affect

	Physical Exercise M (*SD*)	**Control M (*SD*)**	**N**
Ratings of Motivation Before Cognitive Tasks - Pre	5.73 (*1.14*)	5.73 (*1.13*)	16
Ratings of Motivation Before Cognitive Tasks – Post 1	5.76 (*1.27*)	5.74 (*1.13*)	16
Ratings of Motivation Before Cognitive Tasks – Post 2	6.01 (*1.12*)	5.93 (*.94*)	16
Ratings of Motivation After Cognitive Tasks - Pre	5.89 (*1.12*)	5.75 (*1.04*)	16
Ratings of Motivation After Cognitive Tasks – Post 1	5.89 (*1.30*)	5.90 (*1.12*)	16
Ratings of Motivation After Cognitive Tasks – Post 2	5.99 (*1.10*)	6.09 (*1.13*)	16
Ratings of Affect Before Cognitive Tasks - Pre	3.25 (*1.61*)	3.81 (*1.37*)	16
Ratings of Affect Before Cognitive Tasks – Post 1	3.19 (*2.46*)	3.50 (*1.67*)	16
Ratings of Affect Before Cognitive Tasks – Post 2	3.50 (*1.86*)	4.31 (*1.01*)	16
Ratings of Affect After Cognitive Tasks - Pre	3.06 (*1.65*)	3.81 (*1.33*)	16
Ratings of Affect After Cognitive Tasks – Post 1	3.50 (*1.59*)	4.06 (*.93*)	16
Ratings of Affect After Cognitive Tasks – Post 2	3.50 (*1.86*)	4.31 (*1.01*)	16

Figure 1.

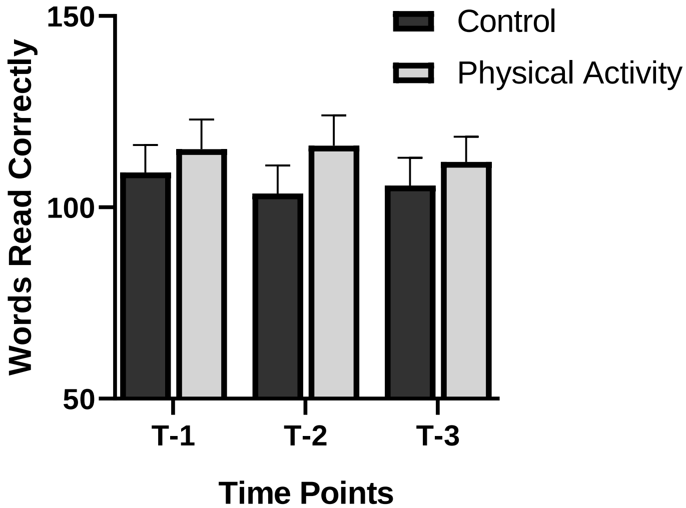

Figure 1. Participants in the Physical Exercise condition read more words during the incongruent Stroop task compared to the Control condition. This pattern was sustained throughout the duration of the experiment. Error bars represent standard errors.

Figure 2.

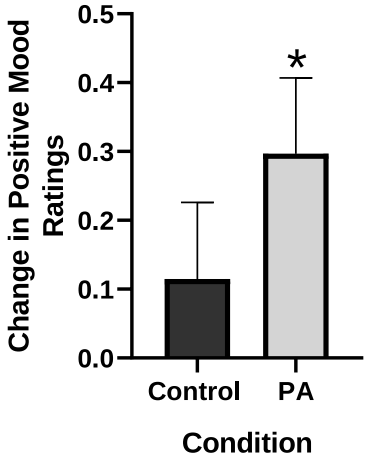

Figure 2. Participants in the Physical Exercise condition had a significant increase in positive mood ratings from the beginning of condition (Time 1) to the end of condition (Time 3). Participants in the Control condition did not show significant increases in positive mood. Error bars represent standard errors.

Figure 3.

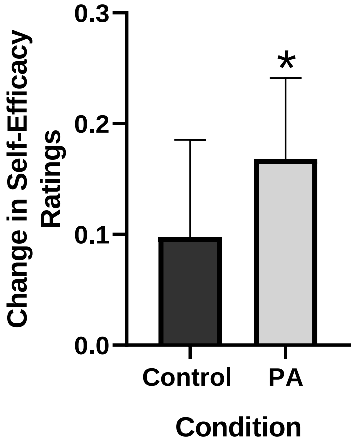

Figure 3. Participants in the Physical Exercise condition had a significant increase in General Self Efficacy ratings from the beginning (Time 1) to the end of experiment (Time 3). Participants in the Control condition did not show significant increases in general self-efficacy. Error bars represent standard errors.

Figure 4.

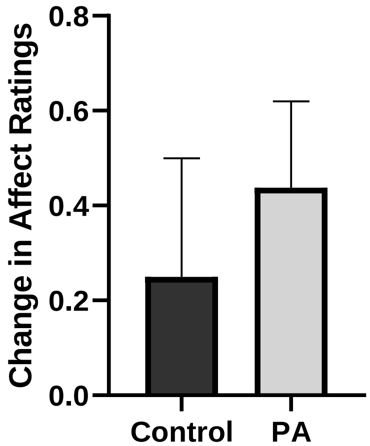

Figure 4. Participants in the Physical Exercise condition had a marginally significant increase ($p = .051$) in Affect ratings following the cognitive tasks from the beginning (Time 1) to post physical exercise (Time 2). Participants in the Control condition did not show significant increases in affect. Error bars represent standard errors.

Table 5
Demographic Information

Characteristic	**Value**
Height (cm), mean (SD)	144.01 (*13.79*)
Weight (kg), mean (SD)	47.15 (*16.16*)
Grip Strength (right; lbs) mean, (SD)	35.91 (*11.08*)
Grip Strength (left; lbs) mean, (SD)	33.73 (*9.77*)
Standing Long Jump (cm), mean (SD)	125.72 (*29.30*)
Age of Parent (years), mean (SD)	47.56 (*7.98*)
Age of Child (years), mean (SD)	11.38 (*1.50*)
Sex of Parent	
Male	7 (43.8%)
Female	9 (56.3%)
Sex of Child	
Male	12 (75%)
Female	4 (25%)
Education	
Some High School	1 (6.3%)
Some College	2 (12.5%)
Trade	2 (12.5%)
Associate Degree	1 (6.5%)
Bachelor's Degree	5 (31.3%)
Master's degree	4 (25%)
Professional Degree	1 (6.3%)
Parent Employment	
Employed for Wages	15 (93.8%)
Homemaker	1 (6.3%)
Parent Income	
20- 30 Thousand	1 (6.3%)
30- 40 Thousand	1 (6.3%)
40- 50 Thousand	1 (6.3%)
50 – 60 Thousand	3 (18.8%)
70- 80 Thousand	3 (18.8%)
80- 90 Thousand	2 (12.5%)
90 – 100 Thousand	0 (0%)
Over 100 Thousand	3 (18.8%)

Prefer not to say	2 (12.5%)

Table 6

ADHD and Medication Status

	Frequency (%)
Diagnosed with ADHD	
Yes	15 (93.8%)
No	1 (6.3%)
Age of diagnosis	
4	1 (6.3%)
6	2 (12.5%)
7	4 (25%)
8	3 (18.8%)
9	4 (25%)
11	1 (6.3%)
Unanswered	1(6.3%)
Age Noticed	
2	1 (6.3%)
3	3 (18.8%)
4	3 (18.8%)
5	2 (12.5%)
6	2 (12.5%)
7	1 (6.3%)
8	3 (18.8%)
Unanswered	1(6.3%)
Prescribed medication	
Yes	3 (18.8%)
No	13 (81.3%)
Currently taking medication	
Yes	6 (37.5%)
No	9 (56.3%)
Unanswered	1 (6.3%)
Medication duration	
6 months	1 (6.3%)
8 months	1 (6.3%)
1 year	1 (6.3%)
1.5 years	1 (6.3%)
2 years	1 (6.3%)
3 years	2 (12.5%)
8 years	2 (12.5%)

Was taking medication recommended by a Doctor?	
Yes	3 (18.8%)
No	4 (25%)
N/A	9 (56.3%)
Why is your child not on medication?	
Concern with side effects	5 (31.3%)
Would prefer alternative treatments	3 (18.8%)
N/A	8 (50%)
If previously medicated, for how long?	
2 years	1 (6.3%)
3 years	1 (6.3%)
4 years	1 (6.3%)
N/A	13 (81.3%)
Any other diagnosis?	
Yes	6 (37.5%)
No	10 (62.5%)
If yes, which ones?	
Anxiety	5 (31.3%)
Mild LD	1 (6.3%)
N/A	10 (62.5%)
Any other medications?	
Yes	2 (12.5%)
No	14 (87.5%)

Table 7

BRIEF and Vanderbilt Results

Characteristic	**Frequency (%)**
Vanderbilt Inattentive	
Yes	13 (81.3%)
No	3 (18.8%)
Vanderbilt Hyperactive	
Yes	8 (50%)
No	8 (50%)
Vanderbilt Oppositional Defiant Disorder	
Yes	8 (50%)
No	8 (50%)
Vanderbilt Conduct Disorder	
Yes	0 (0%)
No	16 (100%
Vanderbilt Anxiety	
Yes	1 (6.3%)
No	15 (93.8%)
BRIEF Inhibition	
Yes	7 (43.8%)
No	9 (56.3%)
BRIEF Self-Monitor	
Yes	10 (62.5%)
No	6 (37.5%)
BRIEF Shift	
Yes	13 (81.3%)
No	3 (18.8%)
BRIEF Emotional Control	
Yes	9 (56.3%)
No	7 (43.8%)
BRIEF Initiate	
Yes	8 (50%)
No	8 (50%)

BRIEF Working Memory	
Yes	10 (62.5%)
No	6 (37.5%)
BRIEF Plan and Organize	
Yes	8 (50%)
No	8 (50%)
BRIEF Task Monitor	
Yes	11 (68.8%)
No	5 (31.3%)
BRIEF Organization	
Yes	8 (50%)
No	8 (50%)

Chapter 4: Discussion

The purpose of this study was to gain a comprehensive understanding of the effects of an acute bout of physical exercise on the neurocognitive and psycho-emotional functioning of children with ADHD. In terms of cognitive functioning, we found that children with ADHD who engaged in a 10min bout of moderate intensity aerobic physical exercise maintained a higher level of inhibitory control (as measured by the Incongruent Stroop Task) compared to when they engaged in 10mins of silent reading. However, we did not find evidence that improved inhibitory control was related to enhanced neural activity in the PFC. We also did not find any benefit of a short bout of physical exercise on sustained attention/task switching or working memory. In terms of psycho-emotional functioning, we found that engaging in a short bout of physical exercise improved ratings of positive mood and general self-efficacy compared to engaging in silent reading. In contrast, there was no benefit of physical exercise for negative mood or motivation, and a marginal benefit for affect. Taken all together, this study showed that a short bout of physical exercise can support inhibitory control, positive mood, and general self-efficacy in children with ADHD.

4.1 Executive Functioning Response to Acute Physical Exercise

In children with ADHD, deficits in inhibitory control are central to the cognitive pathology, and this impairment primarily manifests as impulsive behaviour (Newcorn et al., 2001). Impulsive behaviour severely impairs the ability to maintain focus, filter out irrelevant environmental information, and engage in goal-directed behaviour (Slusarek, 2001). Consistent with previous work, we found that children with ADHD held a consistently higher level of inhibitory control following an acute bout of physical exercise when compared to the silent reading control (Benzing et al., 2018, Chang et al., 2012, Piepmeier et al., 2015). Compared to other domains of executive functioning, it has been suggested that engaging in physical exercise is particularly beneficial for enhancing inhibitory control in children with lower baseline scores. When assessing inhibitory control in typically developing children, Drollette and colleagues (2014) reported that engaging in 20 minutes of physical exercise improved performance only in a subpopulation of children that displayed lower baseline performance. Furthermore, examination of physiological changes in EEG recordings in both groups indicated that P3 amplitude (which suggests greater information processing efficiency) was significantly larger in the lower performers following physical exercise. Taken together, these findings suggest that the potential benefits of physical exercise on inhibitory control could be especially relevant for populations with foundational impairments. However, it has been unclear whether shorter bouts of physical exercise (10 minutes or less) can improve cognitive performance in populations that display these impairments. Identifying this parameter is critical for utilizing physical exercise in school and household settings, ultimately allowing ease of implementation without impacting the time constraints seen in academic and personal settings. Previous reports have identified a minimum of 15-minute bouts to improve inhibitory control (Drollette et al., 2014; Jager et al., 2014). Our work has further elucidated these findings, confirming that an acute, 10-minute bout of physical exercise can buffer against the decline of inhibitory control when compared to silent reading for children with ADHD.

Surprisingly, we did not find improvements in working memory or task switching following physical exercise. Deficits in working memory and task switching are well established in children with ADHD (Fuggetta, 2006), and it has been previously reported that acute bouts of physical exercise can enhance performance on these tasks (McMorris et al., 2011; Barenberg et al., 2015). Specifically, Pesce and colleagues (2009) demonstrated that 40 minutes of acute physical exercise improved working memory in pre-adolescent children with ADHD, while Benzing, Chang, and Schmidt (2018) found that 15 minutes of acute physical exercise improved task switching in 8-12 year old's with ADHD. One explanation for this discrepancy in findings is the duration of physical exercise used. While our physical exercise manipulation supported greater inhibitory control than silent reading, perhaps longer bouts of physical exercise are necessary to improve other domains of executive functioning. As previously mentioned, inhibitory control is the most impaired executive function in ADHD populations. With this considered, it may be that shorter bouts are sufficient for improving the most impaired executive functions, but task switching and working memory require longer durations to manifest improvements.

A second explanation for the discrepancy in findings may reflect the type of physical exercise used across studies. The other studies mentioned implemented physical exercise bouts that included an aspect of cognitive engagement. Pesce and colleagues (2009) used cognitively demanding physical exercise games that included team games, while Benzing (2018) implemented exergaming, a program which required participants to engage in a video game called "shape up" where participants completed a variety of physically and mentally demanding tasks in order to win the game. Cognitively engaging physical exercise includes the addition of a task that requires goal-directed behavior (Crova et al., 2013). Examples of this include individual and team sports, which require the integration of exercise and rapid cognitive processing to successfully plan and anticipate behavior, employ strategies, and adapt to changing task demands. Interestingly, cognitive tasks often used to assess executive functioning place related demands on children's executive processes (Best, 2010). The cognitive demand of complex physical exercise likely increases cognitive engagement, which refers to the allocation of cognitive resources necessary to master and complete a difficult task (Schmidt et al., 2016). This, in turn, may support the enhanced functioning of those cognitive processes on subsequent cognitive tasks due to the pre-activation of the same brain regions. In support of this, Schmidt et al. (2015) compared simple aerobic physical exercise and complex team physical exercise. They demonstrated that the group participating in cognitively demanding physical exercise showed gains in task switching, while the simple aerobic group did not show improvements. Furthermore, studies using other forms of cognitively engaging physical exercise such as aerobic activity while completing math problems, (Vazou and Smiley-Oyen, 2014), the use of exergaming (Benzing et al., 2016), and the use of playful physical exercise games that target executive functions (Jager et al., 2015), demonstrated improvements in inhibitory control, cognitive flexibility and set-shifting. The cognitive engagement experienced during the physical exercise in these studies may require a similar form of thinking and skill, which may then have lingering transfer effects on following executive function tasks (Best, 2010). In contrast, repetitive aerobic exercises (e.g., stationary biking, treadmill walking/running) typically do not require thoughtful consideration during movement to achieve a goal and may therefore, be less cognitively demanding. These differences may explain why complex physical exercise, whether mentally or physically, has a stronger effect on executive functioning. Our future work intends to unpack this issue further by including a cognitively engaging physical exercise condition.

4.2 Prefrontal Cortex Response to Acute Physical Exercise

We found that a single bout of physical exercise did not enhance PFC responses to acute physical exercise. Previous studies using fNIRS have demonstrated that acute bouts of physical exercise elicit subsequently increased prefrontal cortical oxygenation that correlates with enhanced performance on cognitive tasks (Yanagisawa et al., 2010). Similar to our study, Yanagisawa and colleagues (2010) reported enhanced performance on the Stroop Task following an acute bout of physical exercise. However, they also demonstrated a significant increase in PFC oxygenation, specifically in the dorsolateral region (DLPFC). Multiple neuroimaging studies have reported an increase in DLPFC activity during tasks of executive function, especially in children (Morguchi and Hiraki, 2013), while other prefrontal regions such as the left ventrolateral prefrontal cortex do not show increased engagement (Zhiguang et al., 2019). It is possible that our physical exercise session did not impact the prefrontal cortex globally but may have specifically impacted the DLPFC. By sampling the entire prefrontal cortex, we recorded areas whose activity was not increased by PA, or even decreased, therefore diluting potential enhancement in regions like the DLPFC. Our future work aims to refine our analyses to look specifically within the DLPFC.

Furthermore, individual differences in physical fitness may play a role in PFC responsiveness to physical exercise. When comparing studies involving high fit versus low fit individuals, Rooks et al., (2010) found that those who were more physically fit were better able to recruit oxygen to their PFC during physical exercise. In contrast, untrained individuals had a significant decrease in oxygen and blood volume within the PFC following a bout of physical exercise. It is possible that there are individual differences between low and high fit children that may impact how their PFC responds to physical exercise. Our future work will consider physical fitness as an individual difference factor to elucidate whether it impacts the effect of physical exercise on the PFC.

As mentioned above, some research has demonstrated that physical exercise involving more cognitive demands may be more effective for improving performance on cognitive tasks. Recent research also suggests that this combination of cognitive and physical demands may result in greater PFC oxygenation in comparison to each intervention alone. Holzer and colleagues (2011) found that walking while talking increased PFC oxygenation in younger and older adults when compared to just walking alone. In another study by Holzer and colleagues (2015), they found that older adults who walked while they talked had increased PFC oxygenation, which in turn improved performance on cognitive tasks when compared to normal walking. Further, Mirelman and colleagues (2014) discovered that PFC oxygenation was high during walking while counting and was even higher while walking and completing subtraction problems. In contrast, standing still and completing subtraction, as well as just walking alone, resulted in decreased PFC oxygenation. With this considered, it is possible that our purely aerobic physical exercise stimulus was not cognitively complex enough to elicit changes in PFC oxygenation.

4.3 Psycho-emotional Ratings in Response to Physical Exercise

We found that ratings of positive mood and self-efficacy improved following an acute bout of physical exercise. This finding supports previous work showing that engaging in physical exercise significantly improves measures of mood and self-efficacy in both typically developing children and adults, as well as in those with ADHD (Daniel et al., 1992; Cornelius et al., 2017). Despite our work being in line with other research, our study is among the few that have found this outcome with a single short bout of physical exercise in children with ADHD. A randomized control trial conducted by Dishman and colleagues (2004) found that a school-based physical exercise program significantly improved self-efficacy in high school-aged girls when compared to schools not participating in the intervention. A review completed by Cornelius and colleagues (2017) found that both chronic and acute interventions with varying intensities and durations improved mood states in children with ADHD (Hoza et al., 2014; Kiluk et al., 2009; Emmerson, 2010). Supporting self-efficacy and positive mood is beneficial for helping children develop social and communication skills, as well as for helping them develop self-confidence in completing cognitive tasks successfully (Bandura, 2010; Gregory et al., 2012). Though there is research confirming that physical exercise improves both mood states and self-efficacy in children with ADHD, there is little support for a short, single bout. Identifying whether a shorter bout of physical exercise can promote positive mood and self-efficacy for children with ADHD can help support the call for more integration of physical exercise in public domains such as schools and classrooms, which is especially helpful for children who are at heightened risk for low self-efficacy and mood-related disorders. Overall, our findings have built upon existing research to demonstrate that a short 10-minute single bout of physical exercise can support immediate gains in positive mood and self-efficacy in children with ADHD.

Participating in physical exercise did not improve motivation compared to participating in silent reading. Inconsistent with our findings, Sun (2013) found self-reported increases in motivation following a bout of physical exercise in typically developing adolescents. However, Sun's study used exergaming as their physical exercise condition (i.e., the use of video games to exercise). Motivational drive is positively correlated with performance on cognitive tasks, and it may be that the cognitive benefits of more cognitively engaging physical exercise are associated with this general increase in motivation. Another explanation for our lack of findings is that motivation may be less malleable to change after only a 10-minute bout of physical exercise and may require longer durations to change. In support of this notion, previous studies have shown increases in ratings of motivation following longer bouts of physical exercise e.g., 20 minutes (Fritz and O'Connors, 2010), and following chronic routines e.g., ten months (Sun, 2013; Valle et al. 2019). A common hypothesis for increased motivation following physical exercise is the associated release of dopamine, a neurotransmitter associated with reward-motivated behaviour (McMorris et al., 2008). Interestingly, children with ADHD have been shown to have a deficiency in dopamine, which has been suggested to underly motivational deficits when compared to typically developing children (Volkow et al., 2010). Further, it has been demonstrated that physical exercise-induced dopamine release is dependent on the duration of exercise, often requiring durations upwards of 30 minutes (Winter et al., 2007; Hyyppa and Kuusela, 1986). It is possible that this hormone cascade may take even longer in children with ADHD due to their baseline differences in state motivation, and this may explain why we were unable to see improvements in motivation in our sample.

Additionally, our results showed that physical exercise did not significantly improve ratings of affect. However, the results were approaching significance following the cognitive tasks ($p = 0.051$). It is clear that physical exercise did have a positive impact on affect and with more participants, it is possible that we would reach significance. Prior research has consistently shown that physical exercise improves affect in both typically developing children and adults. However, this work has been understudied in populations with ADHD. It has been suggested that the efficacy of interventions targeting affective states is heavily dependent on the baseline affective state of the participant. Specifically, it has been shown that long durations of physical exercise increase positive affect in adults, but not if they have previously been diagnosed with depression (Wichers et al., 2018). Furthermore, it has also been reported that longer durations and higher intensities of physical exercise are required to improve affect in adults with a history of depression when compared to healthy controls (Mata et al., 2012). This is relevant because mood disorders, including depression, are commonly comorbid with ADHD (80%) (Mayes et al., 2008). Although we excluded participants with a formal diagnosis of depression, it is still possible that some participants did indeed have depressive symptoms without confirmation from a doctor. Our future work will consider individual differences in mood and affective states to elucidate whether they impact receptivity to an acute bout of physical exercise.

4.3 Limitations

This study has highlighted important aspects of the impact of a short bout of physical exercise in children with ADHD but is not without limitations. Firstly, we fell a few participants short of our ideal sample size (ideal target of 20, current sample of 16). This may have contributed to some of the lack of significant findings. We also did not have an age-matched control group, which would give better insight into how physical exercise influences those with ADHD compared to typically developing children. Our future research will add an age-matched control to further refine our understanding. Additionally, it is important to mention that some of the participants were on medication for ADHD. Although participants were asked to refrain from using their medication for 24hrs prior to experimental days, it is possible that those on medication differed in their performance compared to those who were not medicated. Children on medication may have a cognitive advantage when compared to children not on medication, ultimately impacting their performance following physical exercise. However, with this considered, Medina and colleagues (2010) compared cognitive performance in children on medication and children not on medication following a bout of physical exercise. Interestingly, they found improvements in cognition following physical exercise irrespective of medication status. Finally, although different versions of the tasks were used each day of the study, it is possible that the results were impacted by practice effects. Despite the potential for practice effects, however, no ceiling effects were observed on cognitive tasks throughout the study, suggesting that participants were not perfecting their performance with practice.

4.4 Implications for Future Research and Conclusion

To our knowledge, this was the first study to examine the neurocognitive and psycho-emotional benefits of a short bout of physical exercise in children with ADHD. Importantly, we demonstrated that an acute bout of physical exercise can have immediate benefits for maintaining inhibitory control functionality and increasing positive mood and general self-efficacy among children with ADHD. These results may increase the accessibility of physical exercise for children with ADHD, providing parents and teachers a feasible, effective tool to be completed in just 10 minutes to assist children cognitively and emotionally, while simultaneously reducing their sedentary behaviour. Importantly, these findings can aid in developing future long-term physical exercise interventions for application in the classroom. Specifically, this study highlights the potential benefits of shorter exercise periods (ie. 10-minute bouts) that could be implemented multiple times per week, as oppose to single 45-minute exercise bouts commonly implemented once per week. Future investigations assessing the potential of this type of exercise regime to benefit cognition and classroom performance would be extremely valuable. Future research should examine the addition of a cognitively engaging physical exercise condition, a larger sample size, the addition of an age-matched control group, and the analysis of the DLPFC's response to acute physical exercise. Nonetheless, this work provides important insight into the impact of a short bout of physical exercise on cognitive and psycho-emotional functioning in children with ADHD and will help pave the way for future research.

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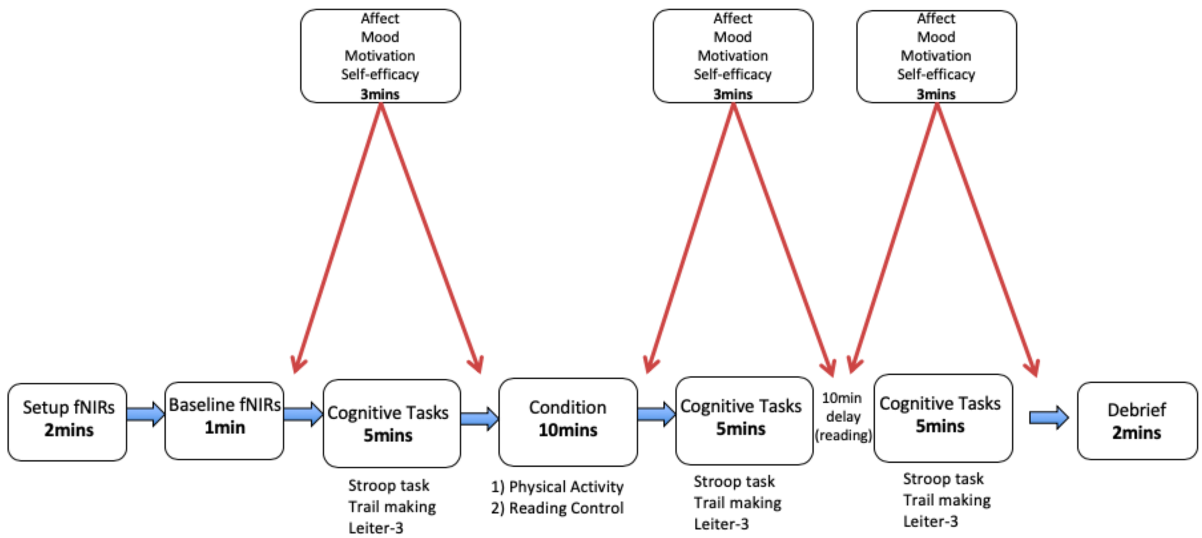
Appendices

Appendix A

Flow of the study



Appendix B

Congruent Stroop Task

BLACK	BLACK
GREEN	ORANGE
BLUE	RED
RED	GRAY
YELLOW	GRAY
ORANGE	GREEN
RED	ORANGE
BLUE	BLACK
ORANGE	BLUE
GREEN	RED
GRAY	BLUE
BLACK	YELLOW
YELLOW	RED

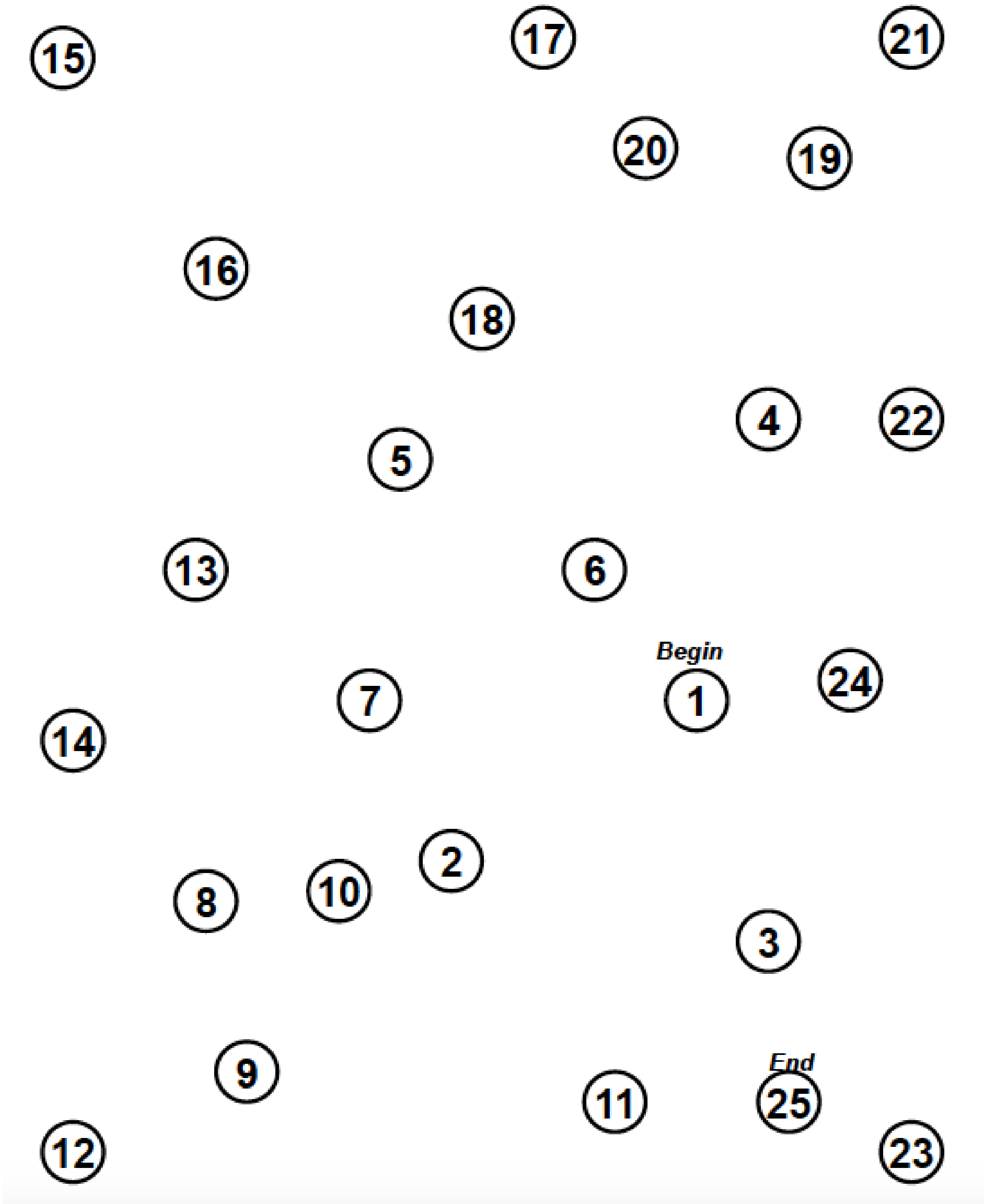
Appendix C

Incongruent Stroop Task

BLACK	BLACK
GREEN	ORANGE
BLUE	RED
RED	GRAY
YELLOW	GRAY
ORANGE	GREEN
RED	ORANGE
BLUE	BLACK
ORANGE	BLUE
GREEN	RED
GRAY	BLUE
BLACK	YELLOW
YELLOW	RED

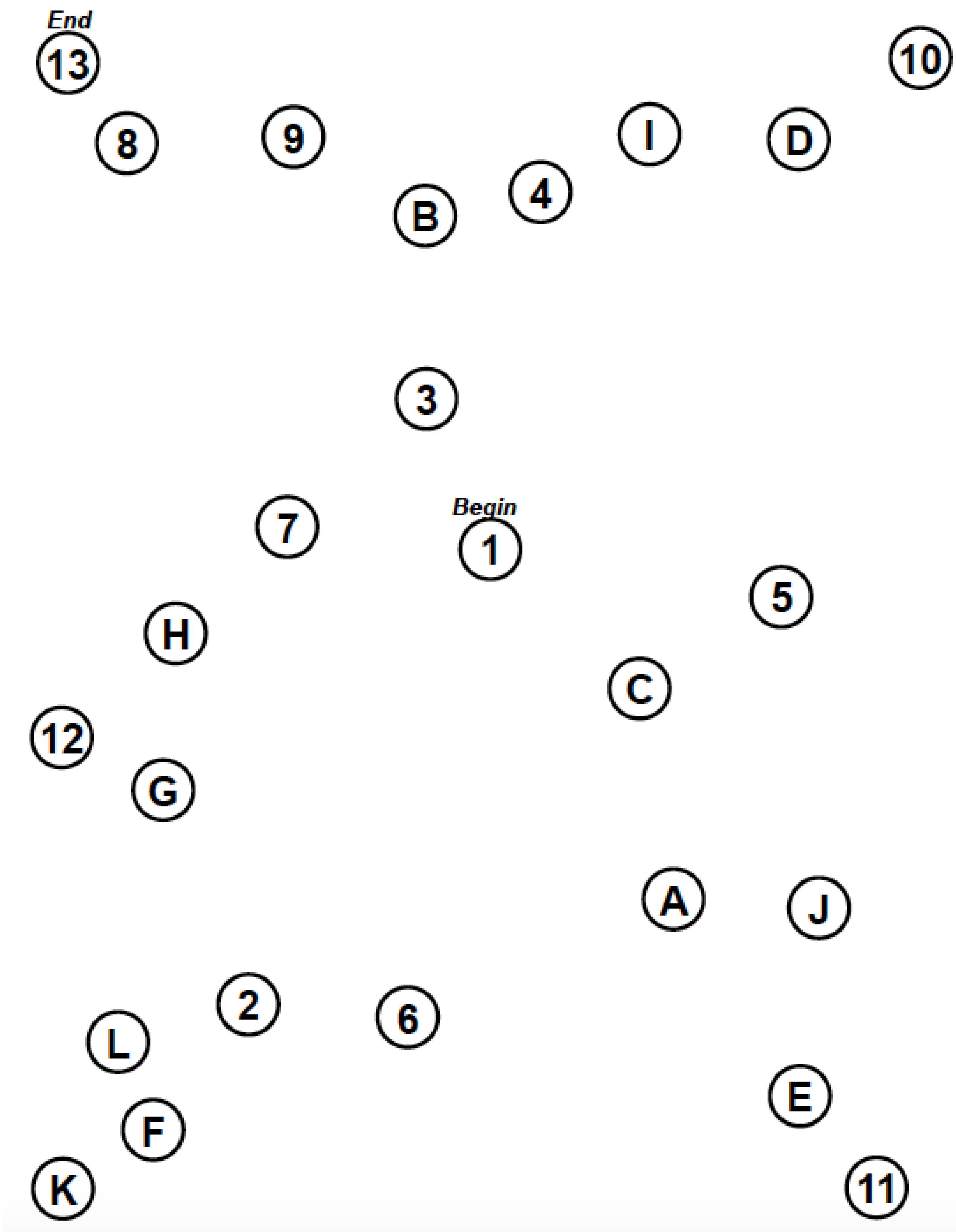
Appendix D

Trail Making A



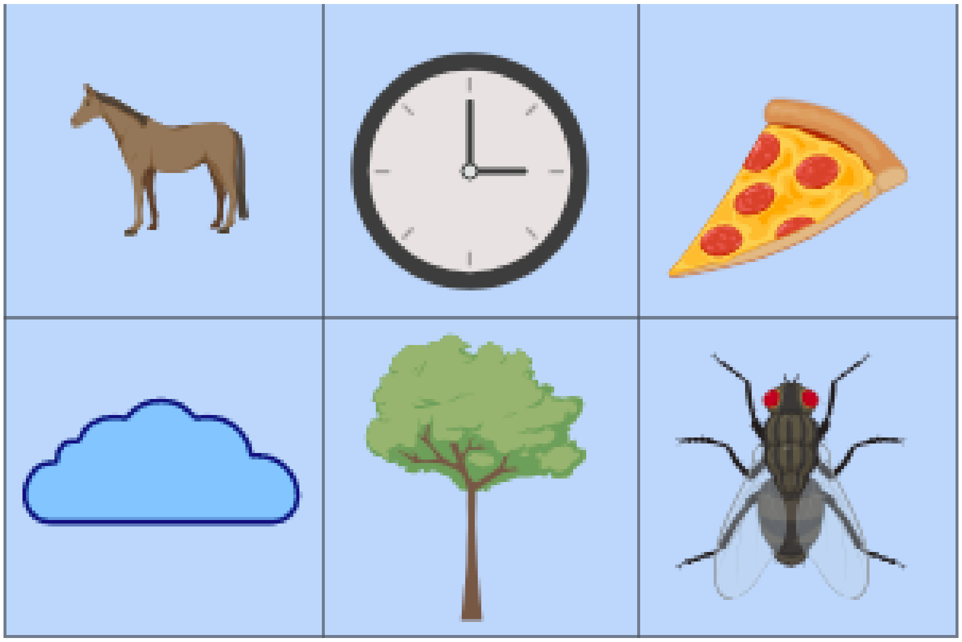
Appendix E

Trail Making B



Appendix F

Working Memory Task



Appendix G

Motivation Questionnaires

Pre-cognitive tasks

For each of the following statements, please indicate how true it is for you, using the following scale:

1	2	3	4	5	6	7
Not at all true		**Somewhat true**			**Very true**	

For the brain games I'm about to do:

1. I am going to put a lot of effort into these brain games. ______
2. I am going to try very hard to do well at these brain games. ______
3. I am going to try very hard on these brain games. ______
4. It is important to me to do well at these brain games. ______
5. I am going to put a lot of energy into these brain games. ______

Post-cognitive tasks

For each of the following statements, please indicate how true it is for you, using the following scale:

1	2	3	4	5	6	7
Not at all true		**Somewhat true**			**Very true**	

For the brain games you just completed:

1. I put a lot of effort into the brain games. ______
2. I tried very hard to do well on the brain games. ______
3. I tried very hard on the brain games. ______
4. It was important to me to do well on the brain games. ______
5. I put a lot of energy into the brain games. ______

Appendix H

Affect Scale

+5	Very good
+4	
+3	Good
+2	
+1	Fairly good
0	Neutral
-1	Fairly bad
-2	
-3	Bad
-4	
-5	Very bad

Appendix I

General Self Efficacy

	Strongly Disagree				Strongly Agree
I will be able to achieve most of the goals I have set for myself	☐	☐	☐	☐	☐
When facing difficult tasks, I am certain that I will accomplish them	☐	☐	☐	☐	☐
In general, I think that I can obtain outcomes that are important to me	☐	☐	☐	☐	☐
I believe I can succeed at most any endeavor to which I set my mind	☐	☐	☐	☐	☐
I will be able to successfully overcome many challenges	☐	☐	☐	☐	☐
I am confident that I can perform effectively on many different tasks	☐	☐	☐	☐	☐
Compared to other people, I can do most tasks very well	☐	☐	☐	☐	☐
Even when things are tough, I can perform quite well	☐	☐	☐	☐	☐

Appendix J

Mood Questionnaire (POMS)

FEELING	Not at all	A little	Moderate	Quite a bit	Extremely
Active	1	2	3	4	5
Awake	1	2	3	4	5
Bored	1	2	3	4	5
Energetic	1	2	3	4	5
Excited	1	2	3	4	5
Friendly	1	2	3	4	5
Happy	1	2	3	4	5
Lonely	1	2	3	4	5
Sad	1	2	3	4	5
Tired	1	2	3	4	5
Unhappy	1	2	3	4	5

Note. Positive mood states were captured by items: Active, Awake, Energetic, Excited, Friendly, and Happy. Negative mood states were captured by items: Bored, Lonely, Sad, Tired and Unhappy.

Appendix K

Ratings of Perceived Physical Exertion (RPE)

Ratings of Perceived ***PHYSICAL*** Exertion (RPE)

Borg, G. (1998). *Borg's perceived exertion and pain scales*. Human kinetics.

0 Nothing at all

0.3

0.5 Extremely weak

1 Very weak

1.5

2 Weak

2.5

3 Moderate

4

5 Strong

6

7 Very Strong

8

9

10 Extremely Strong

11

12 Absolute Maximum

Appendix L

Physical Activity Questionnaire (PAQ-C): Physical Activity in the Last 7 Days

Characteristic	**Frequency (%)**
Skipping	
0	9 (56.3%)
1	4 (25%)
2	1 (6.3%)
3	1 (6.3%)
4	1 (6.3%)
Rowing	
0	15 (93.8%)
1	1 (6.3%)
Inline Skating	
0	15 (93.8%)
1	1 (6.3%)
Tag	
0	5 (31.3%)
1	7 (43.8%)
2	1 (6.3%)
3	2 (12.5%)
4	1 (6.3%)
Walking	
0	3 (18.8%)
1	5 (31.3%)
2	2 (12.5%)
3	3 (18.8%)
4	3 (18.8%)
Biking	
0	7 (43.8%)
1	2 (12.5%)
2	3 (18.8%)
3	4 (25%)
4	
Jogging	
0	6 (37.5%)
1	2 (12.5%)
2	3 (18.8%)
3	3 (18.8%)

4	1 (6.3%)
5	1 (6.3%)
Aerobics	
0	15 (93.8%)
1	1 (6.3%)
Swimming	
0	10 (62.5%)
1	2 (12.5%)
2	3 (18.8%)
3	1 (6.3%)
Baseball	
0	15 (93.8%)
1	1 (6.3%)
Dance	
0	11 (68.8%)
1	2 (12.5%)
2	2 (12.5%)
3	1 (6.3%)
Football	
0	14 (87.5%)
1	1 (6.3%)
2	1 (6.3%)
Badminton	
0	15 (93.8%)
1	1 (6.3%)
Skateboarding	
0	16 (100%)
Soccer	
0	13 (81.3%)
1	2 (12.5%)
2	1 (6.3%)
Street Hockey	
0	16 (100%)
Volleyball	
0	14 (87.5%)
1	2 (12.5%)

Floor Hockey	
0	14 (87.5%)
1	1 (6.3%)
2	1 (6.3%)
Basketball	
0	11 (68.8%)
1	3 (18.8%)
2	1 (6.3%)
3	1 (6.3%)
Ice Skating	
0	15 (93.8%)
1	1 (6.3%)
Country Skiing	
0	16 (100%)
Activity Within Last 7 Days During PE Class	
I don’t do PE	2 (12.5%)
Hardly ever	4 (25%)
Sometimes	4 (25%)
Quite often	3 (18.8%)
Always	3 (18.8%)
Activity During Recess	
Sat down	3 (18.8%)
Stood around	5 (31.3%)
Ran or played a bit	2 (12.5%)
Ran and played quite a bit	2 (12.5%)
Ran and played hard	4 (25%)
Activity During Lunch	
Sat down	10 (62.5%)
Stood around	2 (12.5%)
Ran or played a bit	1 (6.3%)
Ran and played quite a bit	3 (18.8%)
Ran and played hard	
How many days right after school were you active?	
0	6 (37.5%)
1	1 (6.3%)
2-3	4 (25%)
4	2 (12.5%)
5	3 (18.8%)

How many days in the evening were you active?	
0	6 (37.5%)
1	2 (12.5%)
2-3	4 (25%)
4	1 (6.3%)
5	3 (18.8%)
On the weekend how many times were you active	
0	5 (31.3%)
1	2 (12.5%)
2-3	2 (12.5%)
4-5	3 (18.8%)
6 or more	4 (25%)
How often did you do activity on Monday?	
0	2 (12.5%)
1	4 (25%)
2	6 (37.5%)
3	2 (12.5%)
4	2 (12.5%)
How often did you do activity on Tuesday?	
0	3 (18.8%)
1	4 (25%)
2	3 (18.8%)
3	5 (31.3%)
4	1 (6.3%)
How often did you do activity on Wednesday?	
0	2 (12.5%)
1	3 (18.8%)
2	3 (18.8%)
3	3 (18.8%)
4	5 (31.3%)
How often did you do activity on Thursday?	
0	3 (18.8%)
1	3 (18.8%)
2	7 (43.8%)
3	2 (12.5%)
4	1 (6.3%)
How often did you do activity on Friday?	
0	2 (12.5%)
1	6 (37.5%)

2	2 (12.5%)
3	2 (12.5%)
4	4 (25%)
How often did you do activity on Saturday?	
0	6 (37.5%)
1	3 (18.8%)
2	2 (12.5%)
3	3 (18.8%)
4	2 (12.5%)
How often did you do activity on Sunday?	
0	7 (43.8%)
1	2 (12.5%)
2	2 (12.5%)
3	1 (6.3%)
4	4 (25%)

Hannah Bigelow

EDUCATION:

University of Western Ontario **London, ON**
Masters in School and Applied Child Psychology September 2018
Expected completion: June 2020

University of Prince Edward Island
Bachelor of Education **Charlottetown, PE**
Specialized in Primary/Elementary education (kindergarten- grade 6) May 2017- May 2018

University of Prince Edward Island **Charlottetown, PE**
Bachelor of Science with Honours Sept 2012-May 2017
Major in Psychology
Honours in Psychology
First class standing

RECOGNITIONS:

Natural Sciences and Engineering Research Council (NSERC) **2019**
Waitlisted

Ontario Graduate Scholarship (OGS) **2019**
Waitlisted

Stanley Hills Memorial Award **2018**
Awarded to a student graduating from the B.Ed program who, in the opinion of the Dean, shows the most promise of inspirational teaching.

Academic Excellence Award **2016**
University of Prince Edward Island
Awarded to students who maintain and average between 85 and 89.9% during the previous academic year

Academic Excellence Award
2015

TEACHING EXPERIENCE

Pre-Service Teacher **2017**

Athena Consolidated School
Kindergarten
Primary teacher: responsibilities included lesson planning, classroom management, one-on-one work, event coordinating, and student evaluation

Tutor **2014-2018**

Mathematics and Sciences: Grade 4-9
University of Prince Edward Island
PSY-2610 & PSY-2620; Sensation and Perception
PSY-3510; Theories of Personality

VOLUNTEER EXPERIENCE

Let's Talk Science **2019**
Share knowledge with students

Robert Macmillan Symposium **2019**

Mentor **2019**
Mentor for first year Masters of School and Applied Psychology and Counselling Psychology students

Teaching Assistant **2015**
Miscouche Consolidated School
Kindergarten – Grade 5
Assisting children with a variety of disorders including but not limited to; Learning disabilities,
Obsessive Compulsive Disorder, Oppositional Defiant Disorder, Attention Deficit Hyperactivity
Disorder, Conduct Disorder, and Autism Spectrum Disorder

RESEARCH EXPERIENCE

Masters Student **2018**
WEBB Laboratory, Western University
Using fNIRS to investigate the neurobiological mechanisms that underlie the relationship between physical exercise and cognitive function

Graduate Student Assistant **2018**
WEBB Laboratory, Western University
Assisting on research projects in relation to physical exercise and neurobiology

Honours Student **2016-2018**
Neuroscience Laboratory, University of Prince Edward Island
Investigating the effects of environmental enrichment on behavioral endpoints of zebrafish stress response

Volunteer Research Assistant
2017 Neuroscience Laboratory, University of Prince Edward Island
Assisted on an honours thesis project investigating the effects of the light spectrum on behavioral endpoints of zebrafish stress response

Laboratory Volunteer **2015-2016**
Neuroscience Laboratory, University of Prince Edward Island
Assisted in establishing a functional zebrafish laboratory and maintaining the facility

Laboratory Assistant **2015**
Legibility Lab, University of Prince Edward Island
Assisted on a project investigating the implications of different font characteristics on human visual detection
Involved setting up the testing apparatus, recruiting and organizing participants, interacting with the participants, and running the sensory detection test

QUALIFICATIONS

Functional Near Infrared Spectroscopy Training **2019**

Level B assessment **2018**

PRESENTATIONS

Poster Presentation **2019**
Child Health Symposium "The Impact of Physical Activity on Cognitive Function in Children with ADHD"

Poster Presentation **2019**
Child Health Research Day "The Impact of Physical Activity on Cognitive Function in Children with ADHD"

Poster Presentation
European Congress of Psychiatry, Madrid, Spain. "The Impact of Physical Activity on Cognitive Function in Children with ADHD" (Conference cancelled) **2020**

Poster Presentation
Western Research Forum, "The Impact of Physical Activity on Cognitive Function in Children with ADHD" (Conference cancelled) **2020**