JOHNSON, MEGAN N. M.S. No Change in Brain Function or Cognition Following Acute Exercise in Young Adults With Compared to Those Without a History of Sport-Related Concussion: An ERP Investigation. (2022)
Directed by Dr. Eric S. Drollette. 77 pp.

Background: Sport-related concussions continue to impact more than one million US children under 18 years of age annually. Amongst these injuries, long-term cognitive and behavioral consequences are evident in approximately one-third of emerging adults (ages 18 – 29) which may be positively influenced by the mental and brain health benefits associated with acute exercise. As such, it is possible that acute exercise may positively impact these potentially lingering neuroelectric consequences impacting cognitive function in previously concussed emerging adults. Purpose: This study sought to examine (Aim 1) executive function and EEG measures in those with and without a history of concussion at baseline as a function of concussion measured on day 1, and (Aim 2) measure the impact of a single, acute bout of exercise on executive function and EEG outcomes in those with compared to without a history of concussion. Methods: Young adults who have or who are currently participating in non-collegiate competitive sport (n = 25; 18 – 24 years old) visited the lab on two separate days exactly one week apart for approximately two hours to complete a rest and exercise condition that was counterbalanced between participants. Both prior to and following the rest and exercise conditions, participants completed the flanker task with continuous electroencephalogram (EEG) data recorded. Both the cognitive and EEG data were collected to evaluate differences in executive function processes including inhibitory control and the P3 event-related potential (ERP) component (associated with the allocation of attentional resources and the organization and evaluation of stimuli). Results: Results for Aim 1 revealed no differences in attention or inhibition (executive function or P3 outcomes) at baseline between the concussed and non-concussed groups. Results for Aim 2 revealed no changes in executive function or P3 outcomes following acute exercise in those with a history of concussion compared to those without. Conclusion: Current findings suggest emerging adults with a history of sports-related concussions do not experience significant changes to inhibitory control, attentional resources, or P3 components on day 1 or prior to and following an acute bout of exercise. Therefore, regardless of concussion status, acute exercise can continue to be used to improve overall health without negatively impacting these aspects of executive function. Future research should examine how individual differences in exercise, sedentary time, and age of acquiring a concussion may impact this relationship between exercise, cognition, and concussions.

NO CHANGE IN BRAIN FUNTION OR COGNITION FOLLOWING ACUTE EXERCISE IN YOUNG ADULTS WITH COMPARED TO THOSE WITHOUT A HISTORY OF SPORT-RELATED CONCUSSION: AN ERP INVESTIGATION

by

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A Thesis

Submitted to

the Faculty of The Graduate School at

The University of North Carolina at Greensboro

in Partial Fulfillment

of the Requirements for the Degree

Master of Science

Greensboro

2022

Approved by

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APPROVAL PAGE

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October 25, 2021

Date of Acceptance by Committee

May 20, 2022

Date of Final Oral Examination

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my advisor Dr. Drollette for challenging, guiding and supporting me over the past two years. In addition, I am grateful to my thesis committee members (Dr. Etnier, Dr. Monroe, and Dr. Park) for their assistance and suggestions throughout this thesis project and the ENH lab research assistants (Ashley, Sarah, Samantha, Kaden, Abi, Brandy, and Lindsey) without whom this project could not have been completed.

Finally, I would like to thank my family and friends for their constant unconditional love and support as I achieve my dreams.

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CHAPTER I: INTRODUCTION

It is estimated that nearly 1.1 to 1.9 million sports-and recreational-related concussions occur annually in US children under 18 years of age (Bryan et al., 2016). Research reveals that a majority of behavioral and cognitive symptoms that commonly occur immediately following a concussion (e.g. headache, dizziness, irritability, light and noise sensitivity, confusion) resolve within 10 days (Kazl & Torres, 2019) with little to no deficits observed following return to play or persisting into adulthood (Munia et al., 2017). However, long-term consequences are evident with approximately one-third of emerging adults, who sustained a concussion during childhood, experiencing cognitive and behavioral limitations at a time when brain development is expected to reach maturity (Kazl & Torres, 2019), including outcomes related to executive function, or higher order cognitive processing (Caffey & Dalecki, 2021; Cunningham et al., 2020; Karr et al., 2014; Stevens et al., 2012; Tapper et al., 2017). Nevertheless, these lingering limitations related to executive function following a concussion may diminish as a result of engagement in acute bouts of exercise after return to play protocols (Chang et al., 2012; Ishihara et al., 2021). Since recent research on sub-symptom threshold aerobic exercise reveals quicker recovery (Leddy & Willer, 2013) and normalized cerebral blood flow regulation in previously concussed populations (Leddy et al., 2018, 2019) it is possible that acute exercise may improve these possibly lingering cognitive and neurophysiological consequences from a concussion. Thus, combined behavioral and electroencephalogram (EEG) data, may be the best approach to understanding the potential benefits of acute exercise on deficits in underlying brain function. Taken together, this thesis proposal aims to investigate how acute exercise impacts executive function, specifically inhibitory control and attentional processes, in emerging adults with compared to those without a history of sport-related concussions.

Executive function signifies mental processes responsible for adaptable thinking, concentration, attention, and inhibitory control. When concussions are sustained during a developmentally sensitive period, it can negatively impact neuronal activity associated with executive function including inhibitory control (Xu et al., 2017) and attentional resources (Howell et al., 2013; Petley et al., 2018). Nevertheless, a young athletes engagement in acute exercise during and after return to play protocols may benefit inhibitory control and attentional processes (Alosco et al., 2015; Chang et al., 2012; Erlenbach et al., 2021; Hsieh et al., 2018; Ishihara et al., 2021; Kao et al., 2020; Leddy et al., 2018; Ludyga et al., 2016; Pontifex et al., 2019) via shared underlying mechanisms between exercise, cognition and concussions (e.g. neurometabolic cascade, excitatory-to-inhibitory (E/I) balance, and/or the dopaminergic pathway (Giza & Hovda, 2014; Haaf et al., 2018; MacFarlane & Glenn, 2015; Ozga et al., 2018). Taken together, neuroimaging techniques such as event-related brain potentials (ERP's) may offer unique insights into the potentially compensatory effects of exercise on executive function at the neuroelectric level.

ERP techniques can be used to assess neuronal activity associated with aspects of inhibitory control and attentional processes. A common ERP associated with executive function (Donchin, 1981) and examined in a number of past concussion studies (Bernstein, 2002; Broglio et al., 2009; Hudac et al., 2018; Ledwidge & Molfese, 2016) is the P300 or P3 component. It is thought that P3 amplitude reflects the allocation of attentional resources (Polich, 2007, 2012) while latency represents the organization and evaluation of stimuli (Donchin, 1981; Polich, 2012). Research on previously concussed populations reveals reduced P3 amplitude in those with a history of concussion from a few months (Candrian et al., 2018; Gosselin et al., 2012; Lavoie et al., 2004) to years prior (Bernstein, 2002; Broglio et al., 2009; De Beaumont et al., 2009;

Dupuis et al., 2000, 2000) highlighting a deficit in P3 regardless of time since injury. Contrary to these findings, some studies reveal increased P3 amplitude following a concussion compared with healthy controls (Hudac et al., 2018; Ledwidge & Molfese, 2016) and heterogenous results regarding P3 latency where some studies reveal no difference in latency (Dupuis et al., 2000; Hudac et al., 2018) and others revealed longer latencies (De Beaumont et al., 2009; Lavoie et al., 2004; Ledwidge & Molfese, 2016) suggesting an inefficient and potentially compensatory recruitment of neural resources to complete the cognitive tasks. These heterogeneous findings may be due to limitations addressed including small sample sizes possibly impacting statistical results, and individual differences in the number or severity of previous concussions, time since injury, and return to play time following a concussion that may impact EEG measures (Bernstein, 2002; Candrian et al., 2018; Gosselin et al., 2012; Ledwidge & Molfese, 2016). Therefore, these limitations will be accounted for in the current thesis. Although there is no clear consensus on the directionality of the P3 amplitude or latency, it is important for future studies to explore these variations to further determine what may impact the modulation of this component. Furthermore, it is important to note that all studies reveal significant modulation in the P3 for those with a history of concussion compared with healthy controls suggesting neuronal pathways responsible for this outcome are affected by negative consequences of concussion.

Previous research investigating acute bouts of exercise reveal improved inhibitory control or attention processes (Alosco et al., 2015; Chang et al., 2012; Erlenbach et al., 2021; Ishihara et al., 2021; Ludyga et al., 2016; Pontifex et al., 2019), greater P3 amplitude (Hsieh et al., 2018) and decreased P3 latency (Kao et al., 2020) suggesting exercise may positively impact these cognitive and neurophysiological dysfunctions associated with concussion. During and following return to play protocols of a concussion, athletes continue to engage in bouts of exercise including personal exercise routines, practices, and competitions. Researchers have explored the effects of exercise to speed up this recovery process including use of the Buffalo Treadmill Test which is a reliable method to assess exercise tolerance during the acute and post-concussion syndrome phases after a concussion (Leddy et al., 2018; Leddy & Willer, 2013). Additional studies have explored the effects of sub-symptom threshold aerobic exercise during the acute phases of recovery revealing a quicker recovery and normalized cerebral blood flow regulation in concussed populations following aerobic exercise compared to a stretching regimen (placebo) (Leddy et al., 2018, 2019). These studies suggest that acute bouts of exercise are beneficial for reducing symptoms and normalizing reduced cerebral blood flow experienced in concussed populations highlighting the value in exploring how exercise impacts underlying cognitive deficits. Accordingly, this study will utilize ERP and measures of executive function to evaluate to what extent acute exercise may impact potential deficits in executive function and brain function in emerging adults with a history of sport-related concussions.

Purpose and Aims

The purpose of the proposed project is to examine the impact of acute exercise on inhibitory control and attentional processes in emerging adults with and without a history of concussions using a combined behavioral and neurophysiological approach (flanker task performance and EEG measures, specifically the P3). There are two aims of this study: (Aim 1) to assess executive function and EEG measures at baseline (day 1) as a function of concussion history, and (Aim 2) to measure the impact of a single, acute bout of exercise on executive function and EEG outcomes in those with compared to those without a history of concussion.

To accomplish the first aim, continuous EEG data will be collected during a flanker task immediately before the intervention on day 1. The analysis will be done on day 1 regardless of the counterbalanced conditions (exercise or rest), instead of only examining the rest condition, to minimize possible confounding variables that could be experienced on day 2. During the rest session, participants will be instructed to read or study for class for 15 minutes and the exercise condition will consist of a treadmill exercise with self-selected intensities between 9 – 14 on the RPE scale. It is hypothesized that these findings will confirm past knowledge revealing (a) deficits in executive function and (b) decreased P3 amplitude and increased latency at baseline in those with a history of concussion compared to without.

To accomplish the second aim, continuous EEG data will be collected during a neuropsychological measure (from Aim 1) immediately before and after an acute, 15-minute bout of exercise to assess potential alterations in underlying neuroelectric activity and cognitive function. This intervention will occur on a separate day from the rest session. While previous research demonstrates acute exercise can positively benefit the acute phases of a concussion and cognitive function in healthy population, it is unknown how acute exercise will impact underlying brain function in those with a history of concussion. Nevertheless, it is hypothesized that an acute bout of exercise will reveal improved (a) cognitive function and (b) P3 outcome in those with a history of concussion compared to without.

The current proposal holds methodological and practical implications for the potential promotion of exercise in emerging adults with previously sustained concussions. Methodologically, the proposed project focuses on sport-related concussions compared with non-concussed groups as a control measure to increase the certainty that the cognitive and neurophysiological results are due to the independent variables, specifically a history of concussion. That is, this study will provide a more specific understanding of how concussions and acute exercise impact cognitive and neurophysiological outcomes in previously athletic populations. Additionally, the proposed project has important practical applications as understanding how acute exercise impacts underlying function in previously concussed athletes may lead to changes in recovery policies, therapeutic practices, and health standards for those recovering from sport-related concussions. Moreover, it may highlight the need for more extensive research on the neuroelectric dysfunctions that may linger into emerging adulthood long after a concussion was sustained.

CHAPTER II: REVIEW OF LITERATURE

Executive Function

Executive function refers to mental processes that are responsible for working memory, self-monitoring, adaptable thinking, concentration, attention, and inhibitory control (Mackie et al., 2013; Posner & Digirolamo, 1998). When concussions are sustained during a developmentally sensitive period, it can negatively impact underlying mechanisms of neuronal development and communication that supports executive function in everyday life (Cunningham et al., 2020; McGowan et al., 2019; van Donkelaar et al., 2005) including inhibitory control (Xu et al., 2017) and attention (Howell et al., 2013; Petley et al., 2018). Inhibitory control is one's ability to regulate and restrain responses to both target and non-target stimuli (Logan et al., 1997) where attention refers to one's ability to select and concentrate on relevant stimuli in order to make a response (Gardner et al., 1989). The brain structure mainly associated with executive function is the prefrontal cortex (PFC) (Funahashi & Andreau, 2013), but is also supported by superordinate networks including the dorsolateral prefrontal, anterior cingulate and parietal cortices composed of the insular, cingulate, and parietal regions where top-down signaling is used to retrieve information from posterior regions (Niendam et al., 2012) highlighting the importance of cortical interactions between frontal and posterior brain regions (Buss & Spencer, 2018). More specifically, research reveals the medial prefrontal cortex is responsible for attentional processing and cognitive flexibility where the orbital frontal cortex regulates response inhibition. That is, executive function is dependent on cognitive flexibility and efficient neuronal connectivity between networks (Dajani & Uddin, 2015). These studies suggest that the negative neuronal consequences of a concussion may negatively impact executive function outcomes.

P3

Research exploring the effects of concussion on cognitive outcomes have recently begun to investigate potential underlying deficits via event-related potentials. A common ERP used in concussion research and reflective of higher order information and attentional processing is the P3 (Donchin, 1981). This ERP reflects an information-processing cascade associated with the experience of mental events occurring approximately 250 - 500ms following a stimulus onset (Donchin, 1981; Picton, 1992; Polich, 2012; Polich & Kok, 1995) and has revealed modulation of this component when examined in those with neurological cognitive impairments (Polich, 2012). Amplitude is thought to reflect the allocation of attentional resources during stimulus engagement where a larger amplitude is associated with an increase in neuronal activity modulated by internal biological and external cognitive factors (Polich, 2007, 2012). Furthermore, the P3 latency represents the organization and evaluation of stimuli where shorter latencies are associated with quicker processing speeds and superior performance (Donchin, 1981; Polich, 2012). While the most common paradigm to elicit P3 is the oddball task (Picton, 1992; Polich, 2007, 2012), research reveals that additional cognitive tasks can also elicit the P3 including the Stroop (Chang et al., 2017; Chu et al., 2017) and the Flanker tasks (Lind et al., 2019; Parks et al., 2015; Tsai et al., 2018). For instance, a study exploring variability in behavioral and neuroelectric indices of cognition in emerging adults with a history of concussion revealed attenuated P3 amplitude and increased latency is associated with a concussive history during a flanker task with no differences observed in response to an oddball task (Parks et al., 2015).

At the neuronal level, the P3 is associated with neural circuits between the frontal and temporal/parietal lobes which are related to attentional demands of rare/novel stimuli and the promotion of memory operations respectively (Polich, 2012). That is, P3 is generated when focal attention is disrupted by a novel stimuli resulting in a change in neuroelectric patterns in the frontal lobe followed by an activation in the temporal-parietal cortical structures driven by memory storage activations (Polich, 2007, 2012). Additionally, research suggests the P3 is mediated by dopamine levels (Polich, 2007, 2012). That is, since the P3 is regulated by dopaminergic processes (Polich, 2007, 2012), research suggests deficits in the dopaminergic pathway following a concussion may impact executive function and the P3 component.

Concussion

Neurophysiology of a Concussion

A concussion (mTBI) is caused by a blow to the head, neck, or body with impulsive forces transmitted to the head resulting in an onset of short-lived neurological dysfunctions and clinical symptoms (e.g. nausea, dizziness, confusion, and concentration problems) that are not the result of drug, medication use, or any other comorbidities (Aubry et al., 2002; McCrory et al., 2009, 2013, 2017). As stated previously, a significant number of children and emerging adults suffer from short- and long-term consequences of sport-and-recreational-related concussions. Since athletes require quick attentional processing and control during game situations and activities of daily living, these potentially lingering deficits from a concussion may restrict athletes from maintaining the tools needed to process and organize information in fast-paced environments (Tapper et al., 2017). These deficits and restrictions highlight the importance in exploring potential health behaviors that may positively impact the persistent, underlying consequences of this injury in athletic populations.

Immediately following a concussion, there is a rapid shift in the cellular/ionic charges leading to neuronal depolarization (increased permeability resulting in a positive change from a cells resting potential) and (sub)acute alterations in cellular physiology that takes approximately 10 days to return to a cellular homeostatic balance (Giza & Hovda, 2001). As a result of this dysfunction, research reveals acute changes in cognitive and neurophysiological measures (Covassin & Elbin, 2010; Pearce et al., 2015) with approximately 10% of individuals developing post-concussion syndrome (PCS) symptoms or prolonged neurophysiological alterations with cognition deficits in memory or attention (Covassin & Elbin, 2010; Willer & Leddy, 2006). Moreover, these acute and chronic dysfunctions can lead to pathopsychological changes including fatigue, balance, affect, memory, concentration, and judgement (Kazl & Torres, 2019; Wolf & Fast, 2017). Together, neurophysiological and cognitive deficits may persist past the average, 10-day window, highlighting the need to explore underlying dysfunction months to years after the observable symptoms of a concussion subside.

Although research on the long-term effects of a concussion are limited, research reveals those with a history of a single concussion reveal reduced cortical thickness in the left frontal regions which play a vital role in executive function leading to decreased processing speeds (Sussman et al., 2017) possibly due to inefficient neuronal activity. These studies suggest there are long-term concerns following a concussion that are negatively associated with executive function outcomes.

Executive Function and Concussion

Research has explored the relation between executive function and the consequences of a concussion. Past studies exploring concussion-related disruptions to inhibitory control across the recovery period assessed attentional processes in concussed adolescents at various time points post-injury (within 72 hours, 1 week, 2 weeks, 1 month, and 2 months) revealing greater difficulty during Task-switching test up to two months (Howell et al., 2013). An additional study assessed inhibitory control at three separate time points (within 72 hours, after returning to play, and within one month following return to play) revealing deficits to inhibitory control immediately following the injury and up to the one-month marker with no differences at the return to play marker (McGowan et al., 2019). Together, these studies highlight the cognitive limitations evident in emerging adults.

Neurocognitive Outcomes of a Concussion

In terms of behavioral performance, research has used observational research and neuropsychological assessments to explore how concussion impact individuals. One such study investigated NFL athletes returning to play following a concussion compared with controls, who sustained other head and neck injuries, revealing no difference in game on-field contribution and performance in the concussed athletes (Reams et al., 2017). Kuhn and associates completed a similar study exploring changes in style of play and game performance of concussed NHL athletes based on game statistics from pre-to-post injury (e.g. goals, assists, points, shots, penalty minutes, blocked shots, hits, time on ice) demonstrating no changes (Kuhn et al., 2016). Additional studies using neuropsychological assessments have also explored cognitive differences using reaction time, accuracy, and number of errors to reveal an overall equal performance between individuals with a history of concussions and matched controls using working memory (Gosselin et al., 2012) and flanker tasks (Broglio et al., 2009). Contrary to these findings, similar neuropsychological assessments (oddball, working memory, and go/no-go tasks) reveal cognitive deficits on tasks requiring high cognitive demand (e.g. decision making, inhibition, task switching, and/or planning) in those months to years' post-concussion compared to control groups (Caffey & Dalecki, 2021; Ellemberg et al., 2007; Howell et al., 2013; van Donkelaar et al., 2005). Although it is unclear what specifically causes these heterogeneous results in cognitive performances, it is important to note that the majority of studies using neuropsychological assessments reveal deficits in cognition.

Current research on underlying brain function in concussed populations also reveal modulation to ERP's associated with executive function processes including decreased P3 amplitude in those with previous concussions in the past several months (Candrian et al., 2018; Gosselin et al., 2012; Lavoie et al., 2004) and several years (Bernstein, 2002; Broglio et al., 2009; De Beaumont et al., 2009; Dupuis et al., 2000) and increased P3 latencies (De Beaumont et al., 2009; Lavoie et al., 2004; Ledwidge & Molfese, 2016) compared with healthy controls. This research suggests dysfunctions in the P3 are evident regardless of time since injury. For instance, a study by De Beaumont and colleagues (2009) utilized an auditory oddball paradigm to evoke P3 brain responses in former athletes (healthy and previously concussed in young adulthood) to investigate how a sports concussion from thirty years prior impacts cognition revealing significantly delayed and attenuated P3 amplitude and increased latency. This study revealed brain function decline in late adulthood in retired athletes who sustained a concussion more than 30 years earlier in young adulthood (De Beaumont et al., 2009). Nevertheless, some studies have revealed increased P3 amplitude in those with a history of concussion (sample averaged) 2.9 years ago (Hudac et al., 2018) and (sample averaged) 4 years ago (Ledwidge & Molfese, 2016) and no differences in P3 latency (Dupuis et al., 2000; Hudac et al., 2018) compared with healthy controls. These controversial findings may be due to several limiting factors addressed that may influence concussion outcomes including the number and severity of injuries (loss of consciousness or hospitalization), separation of sport from other concussions (falling, vehicle accident), diagnosis including a lack of acknowledging undiagnosed/unreported concussions in the control group (Bernstein, 2002; Candrian et al., 2018; Gosselin et al., 2012;

Ledwidge & Molfese, 2016), and/or brain structure differences in biological sex and increased reporting rates in females compared to males (Covassin et al., 2018; D'Lauro et al., 2018; Stone et al., 2017). These limitations and confounding factors will be measured and accounted for in the current study. Together, this research suggests cognitive deficits may persist at the underlying neuroelectric level following a sport concussion possibly due to the recruitment of compensatory neuronal resources that assist in meeting baseline executive function demands.

Exercise and Concussion

Research reveals various improvements following an acute bout of sub-symptom threshold aerobic exercise during the acute/initial phases of recovery (Leddy & Willer, 2013) including normalized cerebrovascular physiology dysfunctions, and increased exercise tolerance in concussed populations (Leddy et al., 2019). One such study investigating the safety and effectiveness of sub-symptom threshold exercise for post-concussion syndrome (PCS) collected measures of PCS symptoms, heart rate, and systolic blood pressure (SBP) revealing improved exercise tolerance (time exercising and reaching peak HR and SBP) without an exacerbation of symptoms in the exercise treatment group (Leddy et al., 2010). Additionally, the Buffalo Treadmill Concussion Test has been developed to help speed up recovery and return to play for concussed individuals experiencing prolonged symptoms (Leddy et al., 2016; Leddy & Willer, 2013). This aerobic exercise treatment slowly increases exercise exertion until the exacerbation of concussion-specific symptoms occur to identify exercise tolerance through heart rate measurements and subjective exercise intolerance questions (Leddy et al., 2016; Leddy & Willer, 2013). These benefits of acute exercise during the initial phases of recovery may be due to its positive impact on mechanisms that promote neuroplasticity such as the brain-derived neurotrophic factors (BDNF) (Leddy et al., 2018). Taken together, this research demonstrates the positive effect acute exercise has on reducing symptoms and improving physiological responses in the acute/initial phases of a concussion. However, it gives no indication of how underlying cognitive functions are impacted months to years following a concussion which would provide a greater understanding of how these benefits extend past the initial phases of recovery and highlight the possible deficits in the neuroelectric activity related to brain health and cognition.

Effects of Exercise on Cognitive and P3 Outcomes

To date, the majority of research demonstrates positive relations between chronic exercise, cognition (Alderman et al., 2019; Kamijo & Takeda, 2010; Suarez-Manzano et al., 2018; Wilke et al., 2019), and aspects of executive function (Guiney & Machado, 2013; Pesce et al., 2011; Xue et al., 2019). For instance, studies exploring the long-term effects of exercise on cognitive function highlight the positive benefits continual engagements in exercise can have on cognitive decline and function (Chu et al., 2015; Muscari et al., 2010). These studies demonstrate the long-term value chronic exercise brings to preserving cognitive function, suggesting that accumulated bouts may influence cognitive outcomes at the acute level.

While most research reveals improved executive function processing following acute bouts of exercise (Chang et al., 2012; Joyce et al., 2009; Ludyga et al., 2016; Tomporowski, 2003; Verburgh et al., 2014), meta-analysis reveal an overall small but significant cognitive benefit following acute exercise with larger effects influenced by exercise parameters (e.g. light, moderate, and high intensity) and timing between the condition and cognitive assessment (Chang et al., 2012; Chang et al., 2015; Haverkamp et al., 2020; Ludyga et al., 2016; Roig et al., 2013; Verburgh et al., 2014). For instance, research suggests the greatest effects of cognitive performance occur immediately following an acute bout of light-to-moderate-intensity exercise (Chang et al., 2012; Chang et al., 2015; Erlenbach et al., 2021) suggesting acute moderate-intensity exercise improves cognition regardless of what type of cognitive function is assessed. As such, participants will complete the cognitive task immediately following an acute bout of moderate-intensity exercise.

In addition to past studies revealing enhanced cognition following an acute bout of exercise, research also demonstrates enhanced underlying brain function via ERP's in healthy populations. Research repeatedly reveals aerobic exercise is associated with disproportionally larger P3 amplitude (Kao et al., 2020; Ludyga et al., 2017) compared to coordination and resistance exercises (Lind et al., 2019; Ludyga et al., 2017; Wu et al., 2019) with the greatest amplitude achieved following moderate intensity exercise (Kamijo et al., 2004; Kao et al., 2017, 2018) and latency following light or high-intensity exercise (Kamijo et al., 2007; Kao et al., 2018). More specifically, research on the relation between aerobic exercise and P3 reveals increased amplitude and decreased latency in young adults (Kamijo et al., 2007; Ligeza et al., 2018; O'Leary et al., 2011; Won et al., 2017), even when using the flanker task to elicit the P3 (Hillman et al., 2003, 2009; Kao et al., 2017, 2018; Lind et al., 2019; Tsai et al., 2018). These studies suggest that athletes who frequently engage in acute bouts of exercise may experience these exercise-induced cognitive benefits. For instance, Won and associates (2017) examined the underlying effects of three 20-minute sessions of seated rest, treadmill exercise, and a soccer game in a Stroop performance task with continuous EEG collection. This study revealed faster reaction time following both exercise sessions and increased P3 amplitude following the soccer game compared with the treadmill and rest sessions (Won et al., 2017) suggesting enhanced executive function following exercise and sport engagement. Another study explored how variation in sport may alter ERP outcomes revealing that regardless of sport selection, individuals exhibited larger P3 amplitude and shorter latencies compared to the rest conditions

(Aly et al., 2019). Together, these findings highlight how acute bouts of exercise can improve cognitive function in otherwise known healthy populations and athletes suggesting it is possible these benefits are experienced in those with a history of concussion who may face greater cognitive deficits. Unfortunately, there is no published research to date that has explored the effects of acute exercise on cognition or P3 in previously concussed individuals; however, it is possible these acute exercise benefits can be experienced in previously concussed populations as well.

Present Study

In sum, the majority of previous studies reveal little to no differences in observable cognitive performances (reaction time, accuracy, game statistics) (Kuhn et al., 2016; Reams et al., 2017) and mixed findings in studies using neuropsychological measures (Broglio et al., 2009; Caffey & Dalecki, 2021; Ellemberg et al., 2007; Gosselin et al., 2012; Howell et al., 2013; van Donkelaar et al., 2005). However, studies investigating neuroelectric activity via EEG reveal variation in P3 component at rest months (Candrian et al., 2018; Gosselin et al., 2012; Lavoie et al., 2004) to years (Bernstein, 2002; Broglio et al., 2009; De Beaumont et al., 2009; Dupuis et al., 2000) following a concussion. Nevertheless, research demonstrates enhanced cognitive outcomes including inhibitory control and attentional processes (Alosco & Stern, 2019; Chang et al., 2012; Erlenbach et al., 2021; Hsieh et al., 2018; Ishihara et al., 2021; Kao et al., 2020; Leddy et al., 2018; Pontifex et al., 2019), suggesting it is possible these persistent cognitive consequences of a concussion may be minimized as a result of the mental and brain health benefits associated with acute exercise. Moreover, since research reveals quickened recovery rates in those engaging in sub-symptom aerobic exercise during the acute phases of this injury (Leddy et al., 2018, 2019), it is vital to explore how the negative cognitive consequences following a concussion may diminish as a result of engaging in an acute bout of aerobic exercise.

As such, the effects of acute exercise on cognitive outcomes will be evaluated in emerging adults with compared to without a history of a sport-related concussion. To do so, I will confirm past research suggesting deficits in cognition months to years following a concussion (Caffey & Dalecki, 2021; Ellemberg et al., 2007; Howell et al., 2013; van Donkelaar et al., 2005) while revealing a novel understanding of how underlying brain function, specifically inhibitory control and attentional resources, are impacted following the cessation of a single, acute bout of exercise through combined behavioral and neurophysiological (EEG) measures. The completion of this study may assist in shaping health standards and therapeutic programs while highlighting a need to further investigate the neuroelectric dysfunctions associated with cognitive function that may impact brain development and linger into emerging adulthood long after a concussion was sustained.

CHAPTER III: METHODOLOGY

Participants

A total of 36 individuals were recruited for this study at the University of North Carolina Greensboro and the surrounding area through the distribution of flyers, announcements, and emails. In accordance with the Institutional Review Board of the University of North Carolina at Greensboro, individuals willing to release data for research purposes provided consent via digital signature using an online Qualtrics survey (Qualtrics, Provo, UT). Inclusion criteria for the concussed group involved the following: participants must be 18-24 years of age, have a history of at least one sports-related concussion that was sustained between 13-18 years of age with a minimum of 3 months since their last concussion, are not engaging in a collegiate level sport, and were cleared for return-to-play activities where exercise did not exaggerate any previous brain or body injuries. Additionally, those individuals whose concussions were not diagnosed by a physician/doctor were filtered through additional criteria: athletic trainer, coach, or self-diagnoses, and completion of return to play program. If an individual did not meet a minimum of two additional concussion criteria, they were excluded from the study. The control group was non-concussed individuals meeting the same inclusion criteria (age and athletic status) as the concussed group except the history of a sport-related concussion. Although the age of emerging adulthood extends beyond 24 years, I recruited the age group 18 – 24 to restrict the time from injury to allow the history of concussion to be relatively recent given the population I was able to communicate with/recruited from.

Based on the above criteria, four participants did not meet the sport-related concussion criteria but had a concussion making them unqualified for the control group, two were excluded as they did not meet the proposed age requirements, two reported being collegiate athletes, two reported not being an athlete/ever playing sport, and one was excluded as they did not complete both lab visits. As such, a total of 25 participants (n = 11 concussed, n = 14 non-concussed; 18 – 24 years old) were included in the preset study. One participant indicated pre-existing health conditions that would be exacerbated by exercise according to the Physical Activity Readiness Questionnaire (PAR-Q; (Thomas et al., 1992)). This participant received physician’s clearance for the exercise condition but was not able to complete the VO_2 max assessment.

Measures

Demographic and Control Measures

A Qualtrics questionnaire was distributed to assess the participants’ demographics including age and ethnicity/race. Biological sex was also collected as a control variable, especially since females may experience increased neurocognitive impairments and recovery time possibly due to variations in brain structure and higher reporting rates in females compared to males (Covassin et al., 2018; Koerte et al., 2020; Solomito et al., 2019). Additional outcomes were collected as control measures and were evaluated to determine differences between groups. These measures/questionnaires include the following: sleep quality, depression, anxiety, physical activity levels, medication usage, history of sport engagement and sport-related concussions. The Physical Activity Readiness Questionnaire (PAR-Q; Thomas et al., 1992) and Edinburgh Handedness Inventory (Oldfield, 1971) were completed to determine no pre-existing physical or neurological health conditions, and hand dominance, normal or corrected-to-normal vision based on the minimal 20/20 standard.

Concussion History

In addition to demographic information, each participant completed a Qualtrics questionnaire developed to assess eligibility and history of concussion. Since there is no clear standardized post-concussion protocol/measure used in concussion management (Piedade et al., 2021), the survey created for this project was based on questionnaires developed in previous research to assess self-reported concussions in water polo (Blumenfeld et al., 2016) and athletic history in football players (Montenigro et al., 2017). These questions explored time since injury, severity, and recovery for those with and without a history of sport-related concussion while accounting for non-sport-related concussions (e.g. motor vehicle accidents, fights, and/ or falls).

While there does not appear to be a specified window to observe the potentially persistent effects of a concussion, this study explored concussions that were sustained during a developmentally sensitive period between 13 – 18 years of age in emerging adults who are now 18 – 24 years old with at least 3 months from the last sustained concussion. Since research reveals prolonged return to play processes of an average of 29.4 days compared with the most common 10 days in collegiate level athletes (D'Lauro et al., 2018), a minimum of three month will ensure participants have surpassed return to play protocols. Additionally, a maximum six-year window was used to replicate past studies revealing alterations in P3 components following a concussion.

Flanker Task

A modified flanker task was used (Eriksen & Eriksen, 1974) to assess aspects of inhibitory control and attentional resources on a desktop computer through the "PsychoPy" software. Participants responded using a 4-button response pad (Current Designs, Philadelphia, PA), using their thumbs by pressing the left-and-right-most buttons to the directionality of a central arrow presented among four laterally flanking arrows on a computer screen. Both congruent (> > > > > or < < < < <) and incongruent (> > < > > or < < > < <) trial types were included in this task. The stimuli of this study were white arrows presented on a black screen for 100-ms with variable and equally probable inter-stimulus intervals of 1000-ms, 1200-ms, and 1400-ms. Additionally, any response within the first 150-ms was considered impulsive and were included as inaccurate responses in the analysis. To complete this task, each individual engaged in two blocks of 108 trials with equiprobable congruency and directionality both before and after engaging in the bout of exercise and rest session. Practice sessions included 54 trials at the start of each testing day. Interference scores for reaction time (RT) were calculated as incongruent-congruent RT and congruent-incongruent for response accuracy.

ERP Recording

EEG activity was recorded from 64 Ag/AgCl sintered electrode sites organized in accordance with the international 10-10 system (Chatrian et al., 1985) using a Neuroscan Quick-Cap (Compumedics, Charlotte, NC). Prior to recordings, electrodes were filled with conductive gel and impedance maintained <10 kΩ. Online data were referenced to a midline electrode between Cz and CPz with Fz as the ground electrode. To monitor electrooculographic (EOG), vertical (VEOG), and horizontal eye movement, supplemental electrodes were placed above and below the left orbit and outer canthus of each eye. Using Neuroscan SynAmps2 amplifier, online continuous data was digitized at a sampling rate of 1000 Hz, amplified 500 times with a DC to 70 Hz filter, and a 60 Hz notch filter applied.

Offline data was processed using MATLAB (R2017a) with EEGLAB (Delorme & Makeig, 2004) and ERPLAB (Lopez-Calderon & Luck, 2014) toolbox plugins. Data was re-referenced to averaged mastoids (M1, M2). EEG signal was filtered with a high-pass filter of

0.1Hz. In order to identify artifacts associated with eye blinks (Comon, 1994), independent component analyses (ICA) was conducted. After validating their consistency and temporal match with raw VEOG artifacts in continuous EEG data, no more than two ICA components with a correlation coefficient greater than 0.30 were removed.

Stimulus-locked epochs were created at -200-ms to 1200-ms encompassing incongruent trial types. Epochs were baseline corrected using pre-stimulus interval and low-pass filtered at 30 Hz. Epochs were rejected if a moving window peak-to-peak amplitude exceeded 100mV (100-ms window width and 50-ms window step). ERP averaged waveforms were created separately for each trial, condition, and at each time point. P3 latency was quantified using peak latency, and P3 amplitude was quantified using mean amplitude within the post-stimulus latency window 300-ms to 800-ms. Analysis occurred by identifying the sensor with the largest P3 amplitude (i.e., CPz) and then averaging the 9-sensor hot-spot centralized around that sensor (C1, Cz, C2, CP1, CPz, CP2, P1, Pz, P2).

Measures of Exercise Intensity

The Borg Rating of Perceived Exertion (RPE) Scale which has 15 numeric categories ranging from 6 (very light exertion) to 20 (maximal exertion) was used as a subjective measure of exercise intensity (Borg, 1982). Research reveals good reliability and validity of this measure via positive correlations with various physiological outcomes including heart rate, blood muscle lactate concentrations and oxygen consumption during exercise exertion for various age groups (Cabral et al., 2020; Chen et al., 2002; Scherr et al., 2013).

Additionally, participants wore a Polar heart rate (HR) monitor around the torso and watch on either wrist during each lab visit as an objective measure to test the effectiveness of exertion throughout the lab visit. Research reveals accuracy of HR monitors vary with exercise type, but the chest strap monitory (Polar H7) had the greatest association with Electrocardiogram (ECG) on the treadmill compared with Apple watch, the Garmin Forerunner, and the Fitbit Blaze (Gillinov et al., 2017).

Procedure

Using a within- and between-participants pre-post cross-over design, participants completed two two-hour sessions in a laboratory on two separate counterbalanced days that occurred at the same time of day exactly one week apart. Before visiting the lab for testing, participants were required to completed a Qualtrics questionnaire to assess eligibility, demographic information, and history of concussion for descriptive purposes and eligibility requirements. The data obtained from these surveys assisted in determining the non-concussed and concussed groups.

At the beginning of each lab visit, individuals were fitted with a HR monitor and baseline measures of HR and RPE were taken. Participants were then fitted with an EEG cap and completed the flanker task while recording continuous EEG measures. Immediately following this task, individuals completed the exercise or seated rest session, which were counterbalanced between participants, before completing the flanker task again while recording continuous EEG measures. The post-condition flanker task was completed approximately 5 minutes following exercise and rest due to transitioning and re-checking of EEG impedances. During the acute exercise bout, participants were asked to maintain an exercise intensity between 9 (very light) and 14 (somewhat hard) on the rating of perceived exertion (RPE) scale for 15 minutes based on meta-analyses showing the greatest cognitive benefits following acute light-to-moderate intensity exercise (Chang et al., 2012; Chang et al., 2015). If a participant reported an RPE below or above the required range, I reminded them of the instructions and asked them to adjust the treadmill speed and/or incline as needed to fit within that range. During the rest condition, participants were seated in a lab and asked to read or study for class for 15 minutes. This protocol replicates previous findings revealing improved cognitive function following a 15-minute bout of self-selected, aerobic exercise compared to a rest session (studying or reading) of equivalent timing (Johnson et al., 2022). Although it is important to consider context-specific sedentary behavior and improvements in cognition (Loprinzi, 2019), research shows the requirements for this seated rest condition do not impact P3 outcomes (O'Leary et al., 2011; Tsai et al., 2018) suggesting reading/studying should not impact the P3 component. For measures of intensity, HR and RPE were taken at baseline and every three minutes throughout both the exercise and rest conditions to determine study efficacy of separate mean intensive values for each session and ensure participants stay between the required levels for exercise intensity. Additionally, at the end of the rest day, individuals completed a VO_2 max test to determine cardiorespiratory fitness levels between concussed and non-concussed groups given that previous research reveals enhanced P3 components for those with a greater fitness level compared with lower-fit groups suggesting cognitive effects may be dependent on fitness level (Hillman et al., 2006; Tsai et al., 2014).

Data Analysis

Power analysis (G*Power v3.1.9) for Mac OS X (Faul et al., 2007) was performed to determine sample size estimation prior to the collection phase in a repeated measures within-between factors design. Results from previous meta-analytic reports evaluating post-concussion neuropsychological outcomes revealed a moderate (0.4) effect size (Karr et al., 2014) while meta-analysis evaluating cognitive outcomes following a single bout of exercise revealed a small (0.2) to moderate (0.5) effect size (Chang et al., 2012; Haverkamp et al., 2020; Ludyga et al., 2016). Therefore, an average effect size of 0.37 (power = 0.80, and alpha = 0.05) revealed $n = 18$

as the projected sample size for each group necessary to determine an effect. Nevertheless, the current study did not meet the expected sample size for each group. Therefore, a sensitivity power analysis was performed post hoc to determine the strength and reliability of an effect size in the current data set with a sample size of $n = 25$. The minimum effect size that is estimated to reliably detected differences in a within subject *t*-test (power = 0.80, and alpha = 0.05) is $d = 0.51$ (i.e., medium to large effect size) and ANOVA $\eta_p^2 = 0.21$.

Statistical analyses were conducted using SPSS (IBM, SPSS, v. 25). Significant ($p \leq .05$) results and standard error of mean (SEM) will be reported for flanker performance and P3 measures. Repeated measures ANOVA was performed with Bonferroni-corrected *t*-tests including reporting of estimated effect size for repeated measures (Cohen's *d;* small $d = 0.2$, medium $d = 0.5$, and large $d = 0.8$ effect sizes) for post hoc comparisons. For Aim 1, an independent samples t-test was conducted between groups at day 1 (regardless of condition) on flanker performances (RT and accuracy) and P3 amplitude and latency. Flanker analyses was conducted on behavioral (RT and accuracy) interference measures, and congruent and incongruent trial types separately utilizing a 2 (Group: concussion and control) × 2 (Condition: exercise and rest) × 2 (Time: before and after) mixed measures ANOVA. P3 analyses of amplitude and latency was conducted using only incongruent trial types via a 2 (Group: concussion and control) × 2 (Condition: exercise and rest) × 2 (Time: before and after) mixed measures ANOVA.

CHAPTER IV: RESULTS

Demographics

Demographic information of all participants combined and broken down between concussed and non-concussed groups are reported in Table 1. Statistical t-tests were run to ensure these demographic factors were not confounding variables. Results for age, BMI, fitness (mL/kg/min), VO_2 percentile value, sleep quality, anxiety, depression, subjective physical activity and intensity levels revealed no differences between groups (*p's* $\geq .07$, *d*'s ≤ 0.76 see Table 1). Moreover, all participants reported playing competitive sports at any level in the past and ten (concussed 5; non-concussed 5) of those individuals are currently playing sports at a recreational, club and/or intramural level (see Table 1). Additionally, a chi-square test or Fisher's exact test was conducted for categorical variables revealing no differences between groups for gender, sport history, and medication usage (for psychiatric disorders).

Table 1. Demographic Information

Means (± SD), Counts, Independent Samples t-test and Chi-Square Results for Participants' Demographics (All, Concussed, and Non-Concussed)

Measure	All	Concussed	Non-Concussed	*t*	*p*	*d*
n (Female)	25 (17)	11 (8)	14 (9)			
Age	20.76	20.09	21.29			
Race, *n*						
White/ Caucasian	15	8	7			
Black/ African American	8	2	6			
Mixed or Other	2	1	1			
Highest Education, *n*						
High School Graduate	5	3	2			
Some College	16	7	9			
Bachelor Degree	4	1	3			
Number of Competitive Sports Played	2.12 (1.05)	2.55 (1.13)	1.79 (.89)	1.88	.07	0.76
Average Hours in Sport per Week	21.03 (17.83)	22.82 (18.29)	19.62 (18.02)	0.44	.67	0.18
BMI	26.18 (4.84)	25.01 (3.38)	27.01 (5.63)	1.00	.33	0.41
Fitness (mL/kg/min)	25.60 (9.29)	34.28 (7.22)	36.54 (10.70)	0.58	.57	0.24
VO2 percentile value	38.54 (28.58)	34.50 (23.94)	41.43 (32.04)	0.58	.57	0.24
PSQI	8.68 (2.39)	8.36 (2.29)	8.93 (2.53)	0.58	.57	0.23
BDI	7.68 (5.82)	8.91 (6.49)	6.71 (5.28)	0.93	.36	0.38
MVPA	221.80 (129.07)	255.91 (120.50)	195.00 (133.52)	1.18	.25	0.48
STAI	39.80 (17.73)	41.36 (18.86)	38.57 (17.42)	0.38	.71	0.16
Intensity						
During Exercise HR (bpm)	129.37 (25.11)	127.80 (25.96)	130.60 (25.35)	0.27	.79	0.11
During Exercise %HRmax	72.51 (11.51)	71.55 (13.97)	73.20 (9.91)	0.34	.74	0.14

Note: Significant ($p \leq .05$) effects are indicated with *. BMI = Body Mass Index, underweight is below 18.5, healthy weight is 18.5 - 24.9, Overweight is 25 - 29.9, and obesity is 30 above. Fitness and VO2 percentile value were calculated following a VO2 max assessment. PSQI = Pittsburgh Sleep Quality Index, lower scores associated with greater sleep quality (less disturbance) and higher scores associated with decreased sleep quality (severe disturbances). BDI = Beck Depression Inventory, minimal is 0 – 13, mild is 14 – 19, moderate is 20 – 28, and severe is 29 – 63. MVPA = Moderate to Vigorous Physical Activity measured in minutes per week. SAI and TAI = State Trait Anxiety Inventory, no/low anxiety is 20 – 37, moderate is 38 – 44, and high is 45 – 80.

Concussion Assessment

All participants completed a questionnaire to assess concussion status. The counts from the sports related concussion questionnaire are reported in Table 2 for those who qualified for the concussion group (*n* = 11). The majority of individuals in this group sustained their most recent concussion 2 – 4 years ago (*n* = 9), was diagnosed by a physician/doctor (*n* = 7), and waited 7 – 10 days before returning back to play (*n* = 4). The individual who sustained their first concussion between the ages of 7 – 10 had their most recent concussion at age 16, and the two that had their concussion between 11 – 13 had theirs at ages 15 and 16. Additionally, seven (64%) individuals in the concussed group reportedly sustained their first concussion at 16 years old. Those individuals whose concussion was not diagnosed by a physician/doctor (*n* = 3) did not return to play for an average of 7 – 10 days and had completed a return to play protocol. Regarding symptoms following a concussion, majority of individuals (*n* = 10) indicated they experienced symptoms following their concussion and (*n* = 5) indicated they continued to experienced one or more of these symptoms to this day (see Table 2).

Table 2. Concussion Assessment

Sport Related Concussion Questionnaire Counts, n (%)

Question	Concussed Sample
Have you ever sustained a concussion that was diagnosed by a professional in any sport(s)?	
Yes	10 (91)
No	1 (9)
[CDC definition: symptoms]. Based on this, have you sustained a concussion in any sport(s)?	
Yes	10 (91)
No	1 (9)
What was the age at which you sustained your first concussion?	
7 - 10	1 (9)
11 - 13	2 (18)
14 - 17	8 (73)
How many diagnosed concussions have you sustained?	

1	4 (36)
2	4 (36)
3	1 (9)
4+	2 (18)
Was there a year/season in which you sustained more than one concussion?	
Yes	1 (9)
No	10 (91)
Have you ever been admitted to the hospital due to a concussion?	
Yes	1 (9)
No	10 (91)
Have you ever lost consciousness due to a concussion?	
Yes	2 (18)
No	8 (73)
Did you lose consciousness during your most recent concussion?	
Yes	1 (9)
No	10 (91)
Years since most recent concussion	
2 - 4	9 (82)
5 - 7	1 (9)
8 - 10	1 (9)
Who diagnosed your most recent concussion?	
Physician/Doctor	7 (64)
Athletic Trainer	2 (18)
Coach	1 (9)
Myself	1 (9)
After your most recent concussion, how long did you have to wait before returning to play?	
1 - 3	1 (9)
4 - 6	1 (9)
7 - 10	4 (36)
11 - 14	2 (18)
15 - 21	2 (18)
22 +	1 (9)
Have you ever gone through a return-to-play protocol before returning to play in a sport?	
Yes	8 (73)
No	3 (27)
Did you complete a return-to-play protocol for your most recent concussion?	
Yes	6 (55)
No	2 (18)
Did you experience symptoms following your concussion?	
No	1 (9)

1 - 4 symptoms	1 (9)
5 - 8 symptoms	6 (55)
9 - 11 symptoms	3 (27)
To this day, do you continue to experience any of these symptoms?	
No	5 (50)
1 - 4 symptoms	2 (18)
5 - 8 symptoms	2 (18)
9 - 11 symptoms	1 (9)

*The individual reporting ‘No’ in question #1 (sustained a diagnosed concussion by a professional in any sport?) is not the same individual who reported ‘No’ to question #2 (based on CDC definition, have you sustained a concussion in sport?).

Intervention Efficacy

During both exercise and rest conditions, HR and RPE levels were assessed as objective and subjective measures of intensity levels at the following time intervals: baseline, following the first set of cognitive tasks, at 3-minute intervals during the conditions, 5-minutes following the cessation of each condition, and 25-minutes following the cessation of each condition. The during conditions were collapsed across the 3-minute time intervals during each 15-minute condition. The 2 (Group: concussion and control) × 2 (Condition: exercise and rest) repeated measures ANOVA was performed for intervention intensity at each time point (baseline, during, 5-minute post, and 25-minute post) are reported in Figures 1a and 1b. These results revealed no difference between groups at baseline for both HR, but greater RPE levels at baseline for exercise (8.75 ± 0.61) compared to rest (7.85 ± 0.35). Additionally, there was a main effect of Condition revealing greater HR and RPE during exercise (HR: Rest = 75.80 ± 2.15 bpm (min. = 52.00, max. = 93.20), Exercise = 127.35 ± 5.89 bpm (min. = 58.50, max. = 172.40); RPE: Rest = 8.15 ± 0.39 (min. = 6, max. = 12.80), Exercise = 11.01 ± 0.30 (min. = 7.80, max = 13.60), 5-minutes post exercise (HR: Rest = 77.61 ± 2.27 bpm, Exercise = 92.02 ± 3.53 bpm; RPE: Rest = 8.11 ± .40, Exercise = 9.47 ± .47), and increased HR only at 25-minutes post exercise (HR: Rest = 79.76 ± 2.98 bpm, Exercise = 85.52 ± 2.38 bpm) compared with rest, $p \leq .05$ (see Table 3). As such, the total recorded HR (HR during exercise and %HRmax; see Table 2) and RPE measures for both groups were within the required parameters (RPE 9 – 14) during exercise (see Figures 1a and 1b).

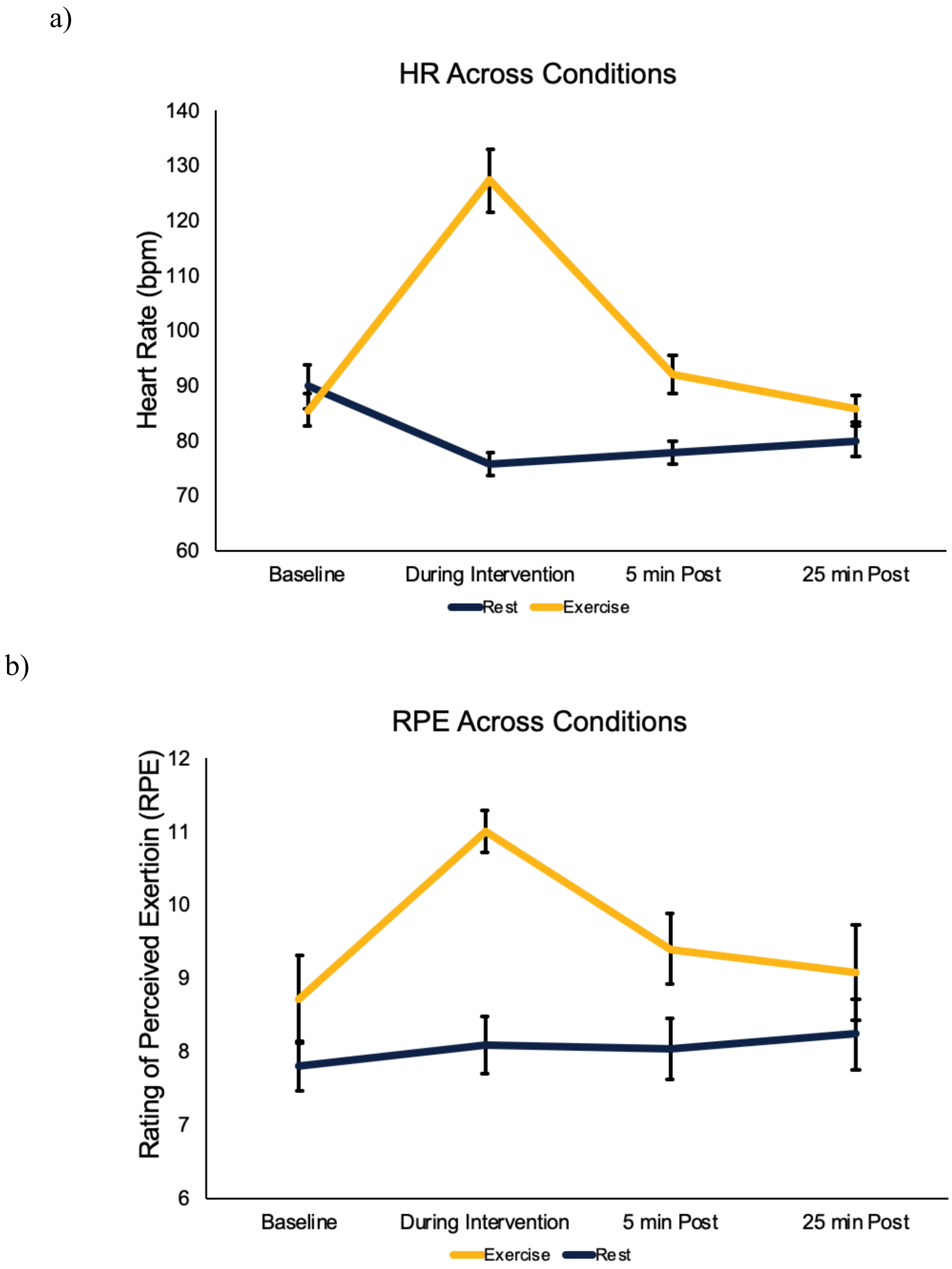
Table 3. HR and RPE Analysis

Summary of Statistical Analysis for HR and RPE scores.

Effect	*F*	df1, df2	*p*
HR			
Baseline			
Concussion	0.78	1, 22	.39
Condition	1.20	1, 22	.29
Condition × Concussion	0.57	1, 22	.46
During Average			
Concussion	0.00	1, 23	.95
Condition	88.33	1, 23	≤.01*
Condition × Concussion	0.01	1, 23	0.93
5 min Post			
Concussion	0.11	1, 23	.74
Condition	25.93	1, 23	≤.01*
Condition × Concussion	0.00	1, 23	.99
25 min Post			
Concussion	0.42	1, 23	.52
Condition	4.40	1, 23	.05*
Condition × Concussion	0.37	1, 23	.55
RPE			
Baseline			
Concussion	0.53	1, 23	.47
Condition	5.52	1, 23	.03*
Condition × Concussion	0.20	1, 23	.66
During Average			
Concussion	1.18	1, 23	.29
Condition	38.09	1, 23	≤.01*
Condition × Concussion	0.84	1, 23	.37
5 min Post			
Concussion	2.46	1, 23	.13
Condition	12.52	1, 23	≤.01*
Condition × Concussion	0.00	1, 23	.99
25 min Post			
Concussion	2.78	1, 23	.11
Condition	2.34	1, 23	.14
Condition × Concussion	0.99	1, 23	.33

Note: Significant ($p \leq .05$) effects are indicated with *.

Figure 1. HR and RPE Across Conditions



Note. Intensity measures of a) Heart Rate and b) RPE evaluated across the Exercise and Rest conditions.

Flanker Performance

Reaction Time and Response Accuracy

The independent samples t-test addressing Aim 1 (flanker performance at day 1 for baseline measures) are reported in Table 4. To address Aim 2, the change in interference scores associated with RT and response accuracy are reported in figures 2a and 2b. Interference scores were used as they are a better representation of inhibitory control (one's ability to suppress inappropriate responses) and decreases the analysis down to a 3-factoral model. Additionally, the statistical results for interference scores, as well as congruent and incongruent trial types separated, are reported in Table 5.

Day 1 Analysis

The omnibus analysis for flanker performance (RT and Accuracy) at day 1 revealed no significant main effect or interactions, *p's* ≥ .07. Additionally, the analysis for P3 amplitude and latency revealed no significant main effect or interactions (*p's* ≥ .27; see Table 4).

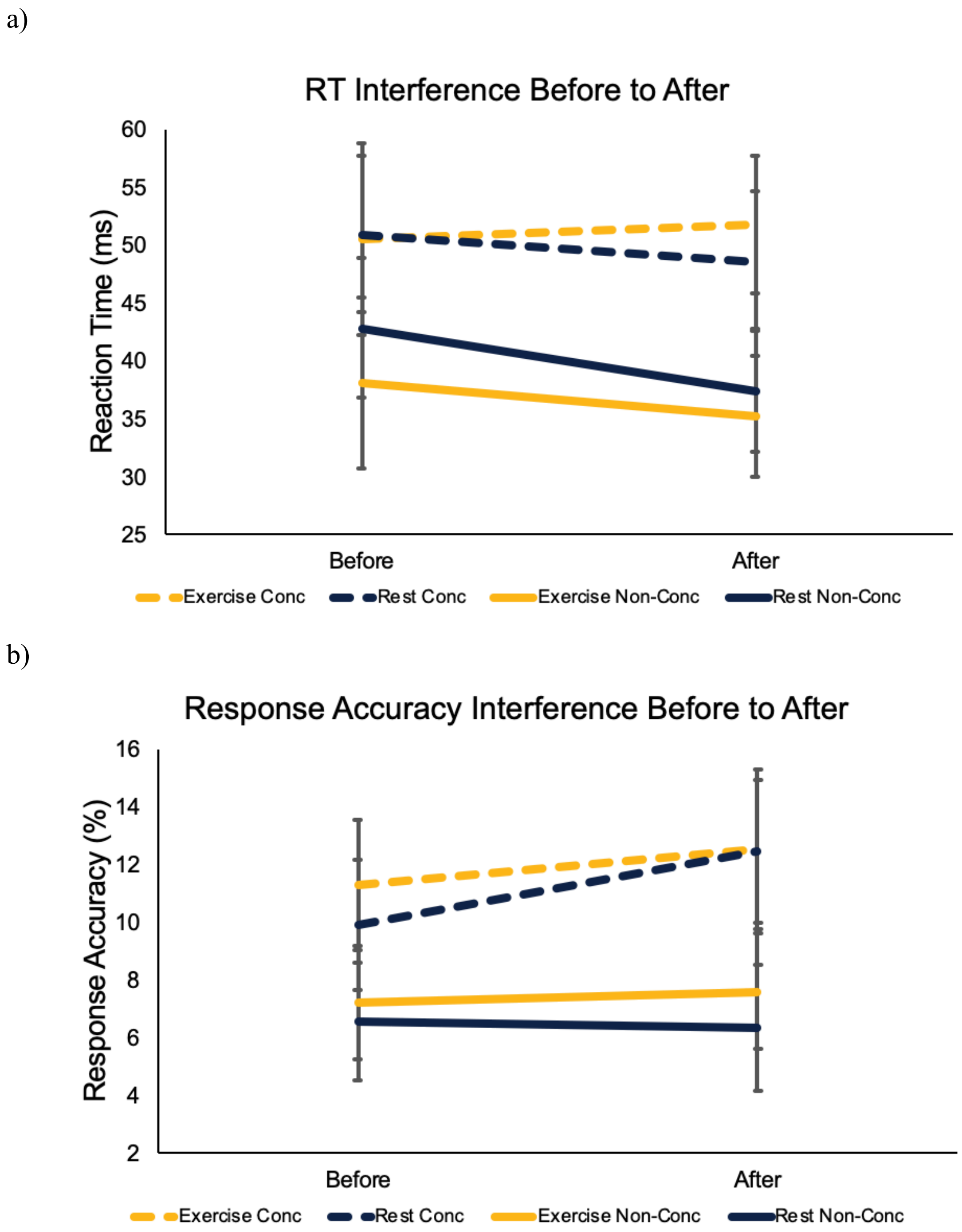
Table 4. Analysis for Flanker Performance at Day 1

Means (± SD) and Independent Samples t-test Results for Day 1 Baseline Performance (All, Concussed, and Non-Concussed)

Day 1 Baseline Measure	All	Concussed	Non-Concussed	*t*	*p*	*d*
Reaction Time						
Interference	52.89 (27.30)	56.51 (33.97)	49.83 (21.08)	-0.59	.56	0.24
Congruent	408.84 (71.88)	438.39 (97.17)	385.61 (30.89)	-1.73	.10	0.77
Incongruent	461.28 (72.97)	494.90 (94.17)	434.86 (36.06)	-2.00	.07	0.89
Accuracy						
Interference	10.80 (8.67)	12.46 (9.35)	9.40 (8.16)	-0.86	.40	0.35
Congruent	96.19 (4.35)	96.72 (2.35)	95.77 (5.50)	-0.53	.60	0.22
Incongruent	85.67 (8.72)	84.26 (9.40)	86.77 (8.33)	0.71	.49	0.29
P3 Amplitude						
Congruent	3.80 (3.30)	3.96 (3.00)	3.70 (3.62)	-0.16	.88	0.08
Incongruent	4.30 (3.76)	4.48 (2.39)	4.18 (4.54)	-0.16	.87	0.08
P3 Latency						
Congruent	410.00 (31.94)	402.60 (28.82)	414.71 (34.26)	0.78	.45	0.38
Incongruent	428.04 (31.23)	417.58 (32.33)	434.70 (30.08)	1.14	.27	0.55

Note: Significant ($p \leq .05$) effects are indicated with *.

Figure 2. RT and RA Before to After Conditions



Note. Changes from before to after the rest and exercise conditions for a) RT and b) response accuracy broken down between concussed and non-concussed groups. A higher RT and response accuracy interference score represents increased difficulty in suppressing inappropriate responses compared with a lower score that represents decreased difficulty when discerning between incongruent and congruent trial types.

Interference

Results for flanker mean RT interference (incongruent-congruent) and response accuracy (congruent – incongruent) revealed no significant main effect or interactions (*p's* ≥ 0.08; see Table 5 & Figures 2a and 2b).

Congruent and Incongruent Trial Types

Results for flanker mean RT and response accuracy broken down between the congruent and incongruent trial types are revealed in Table 5. The omnibus analysis for congruent trials (RT and response accuracy) and incongruent response accuracy reveals no significant main effect or interactions (*p's* ≥ 0.06). However, the analysis for incongruent trials RT revealed a main effect of Time (before 452.11 ± 12.44; after 442.56 ± 11.75) and Concussion Status (concussed 472.68 ± 17.89; non-concussed 421.99 ± 15.86), $p \leq .05$ (see Table 5).

Table 5. Analysis for Flanker Performance

Summary of Statistical Analysis for Flanker RT and Response Accuracy using Interference Scores and Broken Down between Congruent and Incongruent Trial Types.

Effect	F	df1, df2	p	η_p^2
Interference Reaction Time				
Concussion	2.60	1, 23	.12	0.10
Condition	0.07	1, 23	.80	0.00
Time	0.67	1, 23	.42	0.03
Concussion × Condition	0.35	1, 23	.56	0.02
Concussion × Time	0.40	1, 23	.53	0.02
Condition × Time	0.99	1, 23	.33	0.04
Concussion × Condition × Time	0.04	1, 23	.85	0.00
Interference Accuracy				
Concussion	3.45	1, 23	.08	0.13
Condition	0.36	1, 23	.56	0.02
Time	1.12	1, 23	.30	0.05
Concussion × Condition	0.01	1, 23	.93	0.00

Concussion × Time	0.91	1, 23	.35	0.04
Condition × Time	0.06	1, 23	.81	0.00
Concussion × Condition × Time	0.48	1, 23	.50	0.02
Congruent Trials Reaction Time				
Concussion	2.75	1, 23	.11	0.11
Condition	1.07	1, 23	.31	0.05
Time	3.96	1, 23	.06	0.15
Concussion × Condition	0.26	1, 23	.62	0.01
Concussion × Time	0.83	1, 23	.37	0.04
Condition × Time	1.10	1, 23	.31	0.05
Concussion × Condition × Time	0.01	1, 23	.92	0.00
Congruent Trials Accuracy				
Concussion	0.15	1, 23	.70	0.01
Condition	0.44	1, 23	.51	0.02
Time	0.60	1, 23	.45	0.03
Concussion × Condition	0.06	1, 23	.81	0.00
Concussion × Time	0.26	1, 23	.61	0.01
Condition × Time	2.40	1, 23	.14	0.09
Concussion × Condition × Time	2.11	1, 23	.16	0.08
Incongruent Trials Reaction Time				
Concussion	4.50	1, 23	.05*	0.16
Condition	0.88	1, 23	.36	0.04
Time	6.76	1, 23	.02*	0.23
Concussion × Condition	0.58	1, 23	.45	0.03
Concussion × Time	0.16	1, 23	.69	0.01
Condition × Time	0.45	1, 23	.51	0.02
Concussion × Condition × Time	0.06	1, 23	.81	0.00
Incongruent Trials Accuracy				
Concussion	3.91	1, 23	.06	0.15
Condition	0.63	1, 23	.44	0.03
Time	0.58	1, 23	.45	0.03
Concussion × Condition	0.00	1, 23	.96	0.00
Concussion × Time	1.99	1, 23	.17	0.08
Condition × Time	0.80	1, 23	.38	0.03
Concussion × Condition × Time	1.52	1, 23	.23	0.06

Note: Significant ($p \leq .05$) effects are indicated with *.

P3 Amplitude and Latency

The results for P3 amplitude and latency associated with incongruent trial types are reported in Table 6.

Table 6. Analysis of P3 Amplitude and Latency

Summary of Statistical Analysis for P3 Amplitude and Latency with Incongruent trial types.

Effect	*F*	df1, df2	*p*	η_p^2
Amplitude				
Concussed	0.02	1, 22	.88	0.00
Condition	1.44	1, 22	.24	0.06
Time	0.44	1, 22	.51	0.02
Condition × Time	0.71	1, 22	.41	0.03
Concussion × Condition	0.29	1, 22	.60	0.01
Concussion × Time	0.07	1, 22	.79	0.00
Concussion × Condition × Time	0.01	1, 22	.92	0.00
Latency				
Concussed	0.35	1, 22	.56	0.02
Condition	0.17	1, 22	.68	0.01
Time	2.90	1, 22	.10	0.12
Condition × Time	0.34	1, 22	.57	0.02
Concussion × Condition	2.77	1, 22	.11	0.11
Concussion × Time	0.19	1, 22	.67	0.01
Concussion × Condition × Time	0.28	1, 22	.60	0.01

Note: Significant ($p \leq .05$) effects are indicated with *.

Amplitude

The omnibus analysis for P3 mean amplitude revealed no significant main effect or interactions (*p's* ≥ .24; see Table 6).

Latency

The omnibus analysis for P3 latency revealed no significant main effect or interactions (*p's* ≥ .10; see Table 6).

CHAPTER V: DISCUSSION

The present thesis evaluated executive function and P3 (related to inhibitory control and attentional resources) prior to the intervention at day 1 to determine baseline differences between groups. In contrast to my a priori predictions, these data suggest no deficits in executive function or P3 at baseline in those with a history of concussion compared to without. Due to these null findings at day 1, the results fail to reject the null hypotheses (Aim 1). Moreover, these results contradict previous research that suggests those with a concussion experience cognitive deficits on tasks requiring high cognitive demand including attentional processing and inhibitory control (Howell et al., 2013, McGowan et al., 2019; Caffey & Dalecki, 2021; Ellemberg et al., 2007; van Donkelaar et al., 2005). Nevertheless, these findings are in accordance with studies suggesting cognitive performances do not change following a concussion (Gosselin et al., 2012; Broglio et al., 2009; Kuhn et al., 2016; Reams et al., 2017) suggesting there may be an additional factor (i.e. athletic status or engagement in chronic exercise) influencing these concussed samples where executive function remains at a comparable level with the non-concussed group. The data regarding P3 at day 1 are not in line with my hypotheses and are contrary to past research suggesting alterations to P3 components at rest months (Candrian et al., 2018; Gosselin et al., 2012; Lavoie et al., 2004) to years (Bernstein, 2002; Broglio et al., 2009; De Beaumont et al., 2009; Dupuis et al., 2000) following a concussion. Taken together, these findings suggest previously concussed, athletic populations experience no significant alterations to executive function or brain markers of attention and inhibition demonstrating the need to further investigate this relationship between concussion and (neuro)cognition.

Additionally, I investigated the effects of acute exercise on executive function and P3 amplitude and latency in those with a history of concussion compared to those without. Similar to aim 1, these data are in contrast with my a priori prediction revealing no improvements or deficits in executive function or P3 components following an acute bout of exercise. Due to these null findings with the exercise condition, the results fail to reject the null hypotheses (Aim 1). Regarding executive function, these findings contradict those studies proposing an acute bout of aerobic exercise is beneficial for various components of executive function, including attention and inhibition, in otherwise known healthy populations (Chang et al., 2012, Ludyga et al., 2016, Verburgh et al., 2014). Moreover, it contradicts previous findings revealed in a study with similar exercise and rest protocols (Johnson et al., 2022) suggesting attention and inhibition in previously athletic populations with and without a history of concussion are not impacted by acute, self-selected aerobic exercise. Regarding P3, these results are contrary to previous findings suggesting enhanced neurocognition following acute bouts of exercise in otherwise known health individuals (Kao et al., 2020; Ludyga et al., 2017). Nevertheless, these results suggest those with a concussion are not negatively affected by acute aerobic exercise suggesting it may be used as a therapeutic method to improve prolonged symptoms (Leddy & Willer, 2013) and overall health without negatively impacting cognition and brain health.

Although this study demonstrates a history of concussion does not negatively impact executive function and neurocognitive performances, our results are conflicting with alternative concussion research. These conflicting findings may be due to the inconsistent nature of which brain areas are impacted by concussive injuries. Due to the multiple methods of sustaining a concussion (i.e. blow to the head, neck or body with impulsive forces transmitted to the head; McCrory et al., 2017) it is possible there is no one specific area impacted by concussive injury. Although research suggests a common area impacted following a concussion is the midline or corpus callosum (Jang et al., 2019) and that white matter (responsible for communication between regions of the brain and body) is at a higher risk of axonal injury due to its organization and structure (Smith, 2016), the method of acquiring a concussion and subsequent impaired areas varies between individuals (Elkin et al., 2018, Meaney & Smith, 2011). Moreover, research investigating whether the P3 was related to various cortical areas demonstrates the P3 relies more heavily on gray matter compared with white and cerebral spinal fluid (CSF) (Ford et al., 1994) suggesting that even if white matter is impacted following a concussion, it may not directly impact P3 amplitude or latency. Since EEG provides temporal, not spatial, resolution we are not able to determine if certain brain areas remained affected in the concussed group; however, with my null findings it is possible the concussed group sustained injuries where the impaired brain regions were not restricted to the areas or communicating processes related to attentional resources or inhibitory control.

An additional explanation could be the use of a flanker task instead of an oddball task. Although previous concussion research demonstrates deficits in P3 using the flanker (Parks et al., 2015) and it is accepted as an additional task to elicit the P3 (Lind et al., 2019; Parks et al., 2015; Tsai et al., 2018), the auditory and visual oddball task has been used more frequently in concussion research (De Beaumont et al., 2009). As a result, future studies should utilize additional measures supported in research that elicit P3 to determine how task design and difficulty impacts concussed populations.

Furthermore, while this was a within-and-between-subjects design, it should be noted that our data accounted for possible confounding variables mentioned in previous research associated with concussion diagnosis and P3 outcomes (i.e., age, origin of concussion, athletic history, fitness levels, BMI, sleep quality, anxiety, depression, and medication usage) by demonstrating no difference between groups on these measures. Some previous research did not account for these measures which may have implications for the present results. For starters, previous research suggests one-third of emerging adults experience cognitive limitations when brain development is expected to reach maturity following a concussion sustained in childhood (Kazl & Torres, 2019) which was supported in these results (45% experience continued symptoms) suggesting there may not be enough individuals with possibly lingering deficits to demonstrate a significant difference between groups. Additionally, research suggests concussed athletes experience increased levels of depression and anxiety (Covassin et al., 20170817; Solomon et al., 2016); however, our sample demonstrates no differences in these measures suggesting athletes with a history of concussion do not differ from the non-concussed group and may already be experiencing the mental health benefits associated with engagement in exercise (Carter et al., 2021).

That is, previous research suggests chronic exercise has a positive relation with cognition (Alderman et al., 2019; Kamijo & Takeda, 2010; Suarez-Manzano et al., 2018; Wilke et al., 2019), and aspects of executive function (Guiney & Machado, 2013; Pesce et al., 2011; Xue et al., 2019) including attentional resources and inhibitory control. Since both the concussed and non-concussed groups are athletic populations (previously engaged in and/or are currently engaged in sport), it is possible our concussed group has reached their cognitive threshold and are already experiencing the mental and brain health benefits associated with exercise. That is, performance in this sample may be limited by a ceiling effect where improved performance may not have been adequately demonstrated due to peak performances during the rest and exercise conditions. Moreover, it is possible these outcomes are due to cognitive reserve built via engagement in chronic exercise that is protecting their cognitive performances. The cognitive reserve hypothesis suggests the brain is continually coping and compensating from individual differences in cognitive processes where coping skills are improved via premorbid factors including cognitively demanding tasks (i.e., years of completed education) and exercise, that also positively impact cognition (Barnes, 2015; Bigler & Stern, 2015; Donders & Stout, 2019). Thus, it is suggested that those with a higher reserve have improved coping skills compared to those with lower reserves following a concussion (Beaumont et al., 2012; Oldenburg et al., 2016; Stenberg et al., 2020; Wright et al., 2016). Taken together, it is possible engagement in academia and sports during a developmentally sensitive period, throughout emerging adulthood, and following a concussion may positively impact cognitive coping techniques that benefit individuals who may sustain a sport-related concussion to a comparable level of the non-concussed group.

Limitations

Despite the novelty of the present study, there are several limitations worth noting. First, the participants of this study were restricted to previously athletic young adults (18 - 24 years of age) with and without a sport related concussion within the Greensboro, NC area. Due to the specific recruitment of these participants, the generalizability of these results is limited to these specific restrictions (i.e. age, athletic and concussion status) and within this geographical region. As such, future research should continue to explore the effects of this injury on various age groups and modes of acquiring concussions (i.e., vehicle accidents, falling, and/or specific sports) to determine how age and various intensities of this injury may moderate the relationship between exercise and cognition. Secondly, there were several individuals that were excluded due to not having a sport-related concussion or not being within the athletic restrictions resulting in a smaller sample size for both groups. As a result, this study is underpowered. However, based on the main effect of concussion for executive function, the results appear to be trending in the right direction of matching previous research. Therefore, future research should continue investigating the potentially lingering effects of concussions to better understand how this injury progresses months to years following diagnosis. Finally, the timing of the cognitive task following the bout of exercise may have contributed to the null findings. While we attempted to complete the cognitive task 5 – 20 minutes following the acute bout of exercise as suggested in previous research to attain the greatest cognitive benefits (Chang et al., 2012, Chang et al., 2015, Erlenbach et al., 2021), additional studies have investigated cognitive improvements 30 minutes beyond the cessation of exercise (Pontifex et al., 2019) suggesting there are still unknowns regarding the after effects of exercise on cognitive improvements. As a result, future studies should continue to investigate varied timing protocols to further explore how duration shifts the cognitive and brain health benefits and determine how one can maximize these benefits associated with acute exercise, especially in concussed populations.

Conclusion

Overall, these findings suggest that concussions do not appear to negatively impact executive function or neurocognitive performances related to attentional resources and inhibitory control at day 1 of testing or prior to and following an acute bout of exercise. Therefore, these emerging adults who sustained a concussion during developmentally sensitive period do not demonstrate lingering deficits nor improvements to (neuro)cognitive performances suggesting these populations, regardless of concussion status, can continue to engage in exercise for overall health benefits. Taken together, these findings highlight the need for more extensive research to be done on how individual differences in exercise engagement (those who continued sport engagement following a concussion and those who did not) and age of acquiring concussion during various developmentally sensitive periods may moderate the mental and brain health benefits of exercise in previously concussed populations.

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