IMPLICIT MEMORY IN HIGH SCHOOL ATHLETES WITH A HISTORY OF CONCUSSION

By

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ABSTRACT

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Currently, the long-term effects of concussions are not fully understood. Therefore, the current study attempted to explore the relationship between previous concussions and PA with implicit memory in adolescent athletes. For the current study, high school athletes completed a demographic questionnaire, the Physical Activity Questionnaire for Adolescents, and the Serial Reaction Time Task, a measure of implicit memory. Athletes with a history of concussion showed no differences in implicit memory compared to athletes with no history of concussion. Furthermore, current PA was not significantly related implicit memory. Results from this study suggested concussion history did not have an association with implicit memory in adolescent athletes, and current PA level did not have a significant impact on implicit memory acquisition in an active, adolescent population.

ABSTRACT

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PURPOSE: Currently, the long-term effects of concussions are not fully understood. Some research has demonstrated continued decrements in neurocognitive performance in both pediatric and adult populations, including memory tasks, in those athletes with a history of multiple concussions. With implicit memory, an individual will know how to complete a task, but may be unaware of this knowledge. While much research has been conducted on the relationship between physical activity (PA) and improved performance on tasks of explicit memory and executive function, no research currently has explored PA and implicit memory. Therefore, it is appropriate to consider the role PA may have in the relationship between concussion history and performance on a cognitive task of implicit memory. The purpose of this dissertation was to examine the differences in scores of implicit memory acquisition across concussion history groups (i.e., no concussion, one or more previous concussion(s)) and across current levels of PA.
METHODS: The study design was cross-sectional. The independent variables were concussion history and PA. The dependent variable was a measure of implicit memory acquisition. All participants were high school athletes, both male and female, between the ages of 13 and 19 years. Athletes were grouped together based on their concussion histories (i.e., no previous concussion, one or more previous concussion(s)). PA was assessed by the Physical Activity Questionnaire for Adolescents (PAQ-A) and scored as a continuous variable, resulting in a score of one to five. Implicit memory was measured using the Serial Reaction Time Task (SRTT).

Demographic variables including age, height, weight, sex, race/ethnicity, and approximate grade point average, as well as concussion history, were obtained via a demographic form completed by the participant. **RESULTS:** A total of 64 high school athletes (29 female, 35 male) participated in the current study, 46 (25 female, 21 male) had no history of concussion, compared to 18 athletes (4 female, 14 male) with a history of at least one previous concussion. Overall, the findings suggested a history of concussion was not related to implicit memory acquisition in adolescents, $F(1,50) = .250$, $p = .619$, adj. $R^2 = .015$. Furthermore, current PA was not significantly related to performance on the SRTT ($F(1,48) = 1.543$, $p = .220$, adj. $R^2 = .011$). Finally, there was no interaction of concussion history and PA relative to implicit memory. **DISCUSSION:** While previous research has demonstrated deficits in implicit memory acquisition in previously concussed, asymptomatic adults, the current study did not replicate these results in an adolescent population. Additionally, implicit memory was not associated with current PA. These findings suggest, in adolescents, concussions may not be associated with implicit memory acquisition.

This dissertation is dedicated to my family and friends for their continued love and support.

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CHAPTER 1

INTRODUCTION

1.1 Overview of the Problem

It is estimated that between 1.6 and 3.8 million sport-related concussions (SRC) occur annually (Langlois, Rutland-Brown, & Wald, 2006). Many researchers and medical professionals agree that this estimate may be under-representative, due to failure to report and diagnose suspected concussions and the lack of a national surveillance system. Participation in high school sports has continued to increase for the 24th straight year for both males and females, with over 7.7 million participants nationally during the 2012-2013 school year (*National Federation of State High School Associations Handbook: 2012-2013 High School Athletics Participation Survey,* 2013). With this increase in participation, an increase in the diagnosis of concussions has also been demonstrated, from a rate of 0.23 to 0.51 between 2006 and 2012 (Rosenthal, Foraker, Collins, & Comstock, 2014).

Furthermore, some previous research suggests those athletes with a history of concussions have a higher relative risk of incurring a subsequent concussion (Gerberich, Priest, Boen, Straub, & Maxwell, 1983; Guskiewicz, Weaver, Padua, & Garrett, 2000; Guskiewicz, et al., 2003; Zemper, 2003). Some research suggests the relative risk of sustaining a concussion may only be greater in those athletes with a history of concussion based on their style of play, suggesting athletes who engage in illegal techniques such as face-tackling and butt-blocking, may be at a higher risk for subsequent concussions (McCrory, Johnston, Mohtadi, & Meeuwisse, 2001). Additionally, research has demonstrated more symptoms in the acute phase of recovery for those athletes with a history of 3 or more previous concussions, including greater loss of consciousness (LOC), more anterograde amnesia, and more confusion (Collins, Lovell, Iverson, Cantu, Maroon, & Field, 2002). When exploring recovery from concussions, research has suggested a more protracted recovery time for those athletes with a history of concussion (Collins, et al., 2002; Covassin, Moran, & Wilhelm, 2013; Eisenberg, Andrea, Meehan, & Mannix, 2013; Guskiewicz, et al., 2003; Covassin, Stearne, & Elbin, 2008; Slobounov, Slobounov, Sebastianelli, Cao, & Newell, 2007). This slowed recovery time has also been demonstrated utilizing virtual reality to measure visual-kinesthetic integration recovery (Slobounov, et al., 2007), suggesting that a more broad evaluation of recovery should possibly be utilized.

Similarly, some research demonstrated continued decrements in neurocognitive performance in those athletes with a history of multiple concussions (Covassin, Elbin, Kontos, & Larson, 2010; Iverson, Echemendia, LaMarre, Brooks, & Gaetz, 2012; Iverson, Gaetz, Lovell, & Collins, 2004; Master, Kessels, Lezak, Jordan, & Troost, 1999; Moser & Schatz, 2002; Moser, Schatz, & Jordan, 2005; Schatz, Moser, Covassin, & Karpf, 2011; Guskiewicz, Marshall, Bailes, McCrea, Cantu, Randolph, & Jordan, 2005). However, the research remains inconclusive on this point, as other studies have found no significant differences in neurocognitive recovery in athletes with a history of multiple concussions (Broglio, Ferrara, Piland, & Anderson, 2006; Bruce & Echemendia, 2009; Collie, McCrory, & Makdissi, 2006; Iverson, Brooks, Lovell & Collins, 2006; Macciocchi, Barth, Littlefield, & Cantu, 2001). Therefore, more research must examine the difference in neurocognitive recovery between those with a history of concussion and those without a history of concussion.

Recent research has focused on Chronic Traumatic Encephalopathy (CTE), a neurodegenerative disease resulting from repetitive mild brain trauma (McKee, et al., 2009; McKee, et al., 2010; McKee, et al., 2013; Stern, Riley, Daneshvar, Nowinski, Cantu, & McKee, 2011). Often, CTE will present clinically with impairments in memory, cognition, mood, and behavior (McKee, et al., 2013; Stern, et al., 2011). CTE typically does not present until many years after the repetitive brain trauma has ceased (Stern, et al., 2011). While research on CTE and its link to repetitive brain trauma is still in its infancy, it is evident research should continue to explore the cumulative effects of multiple brain injuries.

Furthermore, very little research to date has explored implicit memory following concussion. Implicit memory decrements may lead to a failure by athletes to link consequences to actions, potentially increasing the risk for subsequent injury. The research that has been done was conducted with adult populations and demonstrated markedly reduced implicit memory via the Serial Reaction Time Task (SRTT) in those athletes with a history of concussion compared to control athletes with no history of concussion (De Beaumont, Tremblay, Poirier, Lassonde, & Theoret, 2012; De Beaumont, Tremblay, Henry, Poirier, Lassonde & Theoret, 2013). In fact, these decrements were seen in athletes as far out as 37 years since their last concussion (De Beaumont, et al., 2013). At this time, no research has been performed examining the effect of concussion on implicit memory in an adolescent population.

Numerous studies have been conducted on the relationship between physical activity (PA) and cognition, including many meta-analyses (Colcombe & Kramer, 2003; Sibley & Etnier, 2003; Smith et al., 2010; Fedewa & Ahn, 2011). The majority of research indicates there is a direct relationship between both acute and chronic PA and cognitive function. Overall, regardless of the specific task, higher levels of PA can increase cognitive performance. Furthermore, aerobic fitness is positively related to implicit memory acquisition in college students (Pontifex, Parks, O'Neil, Egner, Warning, Pfeiffer, & Fenn, 2014). Given these findings, it is appropriate to consider the role PA may have in the relationship between concussion history and performance on a cognitive task of implicit memory.

1.2 Significance of the Problem

The long-term effects of concussions are not fully understood. Therefore, it is expected that this dissertation could provide new understanding of the role that concussions have in respect to implicit memory during adolescence. Implicit memory may be expressed as associative learning, or the idea of linking behaviors to consequences. If implicit learning is impaired in athletes with a history of concussion, these athletes may lack the ability to link consequences to actions (Bear, Connors, & Paradiso, 2007). This can be especially problematic when the lack of associative learning is reflected by risk taking. An athlete who has impaired procedural memory may put himself in a more vulnerable situation, thereby increasing his risk of future injury.

Additionally, if implicit memory is found to be associated with a history of concussion, given our knowledge of the procedural memory system, we may hypothesize that certain sub-cortical regions of the brain, such as the basal ganglia, may be impaired. Developmentally speaking, these regions seem to be mature by adolescence; however, insults may still affect the brain's ability to learn and master new tasks. Therefore, by investigating implicit memory, we may be able to gain a better understanding of the pathophysiology of concussions.

1.3 Purpose of the Study

The current study considered adolescents' implicit memory, while also considering the role of concussion history and PA. Therefore, the purpose of this dissertation was to examine the differences in scores of implicit memory acquisition across concussion history groups (i.e., no concussion, one or more previous concussion(s)) and across PA.

1.4 Specific Aims and Hypotheses

Specific Aim #1: Determine the relationship between concussion history (i.e., no previous concussion, one or more previous concussion(s)) and implicit memory acquisition in adolescents.

Hypothesis 1: Concussion history would be inversely related to implicit memory acquisition.

Specific Aim #2: Determine the relationship between PA and implicit memory acquisition in adolescents.

Hypothesis 2: PA and implicit memory acquisition would be positively related.

Specific Aim #3: Examine the potential interaction between current level of PA and concussion history on implicit memory acquisition in adolescents.

Hypothesis 3: PA would protect against concussive effects on implicit memory acquisition.

1.5 Definitions Used in this Study

Concussion. Concussion was broadly defined based on self-reported previous diagnosis by an athletic trainer or physician. No formal definition will be given for concussion.

Concussion history. Based on answers to questions on the demographic form (see Appendix A), an athlete's concussion history was defined as the number of previous concussions diagnosed by an athletic trainer or physician. Athletes were then separated into the following groups representing concussion history: no previous concussion, one or more previous concussion(s).

Implicit memory. Implicit memory was defined as various types of remembering such as motor-skill learning, priming, and condition, and is beyond what is consciously remembered. Implicit memory was measured using the SRTT.

Physical activity. For the purpose of the current study, PA was defined as any bodily movement that results in energy expenditure, and was measured via the Physical Activity Questionnaire – Adolescent version (see Appendix B).

Serial Reaction Time Task (SRTT). Implicit memory was measured using the SRTT, which is a four-choice reaction time (RT) sequence. Embedded within the task is a repeating sequence.

Physical Activity Questionnaire for Adolescents (PAQ-A). The PAQ-A is a measure of PA in adolescents. It is a self-report questionnaire resulting in a score of 1 to 5, representing the athlete's level of PA over the past seven days. For the purposes of the current study, PA was scored as a continuous variable, on a scale of 1 to 5.

1.6 Limitations

The current study was not without limitations. Utilizing self-report for concussion history may prove to have limited our findings, as we relied on the respondents answering truthfully and completely. By specifying the concussion should have been diagnosed by an athletic trainer or physician, some obscurity in reporting past concussions may have potentially been avoided. However, some potential concussions may not have been formally diagnosed, thereby limiting the number of concussions reported.

1.7 Assumptions and Delimitations

In conducting the current study, certain assumptions were made. Most notable, when utilizing survey measures, it was assumed that participants would answer truthfully and completely. In order to best ensure participants felt comfortable in answering truthfully, anonymity and confidentiality were preserved. Furthermore, participants were instructed on their ability to withdraw at anytime or pass over questions they preferred not to answer. It was also assumed that cumulative effects from concussions would continue to be of interest in the research community and the community at large. Given that the Centers for Disease Control and Prevention recently declared SRC to be a serious public health concern, it is probable to assume that concussions and concussion research will continue to be in the forefront of public health.

For the current study, PA was measured utilizing a self-report survey rather than another measure of PA, including primary measures (e.g., direct observation) and secondary measures (e.g., accelerometers). This tertiary measure of PA was chosen based on its availability and accessibility for the participants. Likewise, while other measures exist for assessing implicit memory, the current study used the SRTT, as it has been extensively used in research previously, and showed to be sensitive to small, yet significant differences in RT.

The sample used in the current study was a convenience sample. That is to say participants were recruited from local high schools, and therefore may not be representative nationally. All participants were high school athletes and as such, may not represent the non-athlete, high school population.

CHAPTER 2

REVIEW OF LITERATURE

2.1 Introduction

This review of literature examines the current research in several areas related to the current study including: an extensive examination of concussions, the relationship between physical activity and cognition, and an overview of the memory systems, with a detailed assessment of implicit memory. The overall purpose of this literature review is to discuss thoroughly researched effects of concussions, as well as introduce a possible new effect of concussion on implicit memory. An overview of concussions including the epidemiology, definition, biomechanical aspects, pathophysiology, signs and symptoms, age differences, and cumulative effects of concussion is first introduced, followed by an examination of the effects of physical activity on cognition and memory. The remaining variable of implicit memory is then discussed with specific attention to the possible relationship between SRC and implicit memory.

2.2 Epidemiology of Concussion in High School Athletes

According to the National Federation of State High School Associations (NFHS), participation in high school athletics for the 2012-2013 school year increased from previous years, passing 7.7 million participants nationally. The NFHS number of female participants increased to over 3.2 million and male participants made up approximately 4.5 million. Overall participation in high school athletics has increased for the 24th straight year (*National Federation of State High School Associations Handbook: 2012-2013 High School Athletics Participation Survey*, 2013). With the continued increase in participation in athletics, the high school population is of interest for research on concussions and PA.

In 1998, the Centers for Disease Control and Prevention (CDC) estimated that approximately 300,000 SRC occur annually. Since then, the incidence has been re-estimated by the CDC to be between 1.6 and 3.8 million SRC annually (Langlois, et al., 2006). However, it is difficult to get an exact representation of the incidence of concussions nationally. At this time there is no national surveillance system in place where concussions are reported and recorded; therefore, all numbers representing the incidence of concussions are estimates. Certified athletic trainers, primary care physicians, emergency room doctors, or specialty doctors may all have the opportunity to treat concussions, therefore strictly utilizing emergency room visits to quantify concussion incidence and prevalence, as many previous studies have done, may be inadequate.

There are many different definitions of concussion in place today, and the definition has shifted over time, allowing for a more broad view of what constitutes a concussion, no longer requiring a LOC to have occurred. As a result of the many definitions in use, a considerable problem arises in that many people may not be able to recognize a true concussion. Previous research has demonstrated that many concussions go undiagnosed and underreported due to lack of knowledge surrounding what comprises a concussion by athletes and coaches involved in sport (Delaney, Lacroix, Leclerc, & Johnston, 2002; Kaut, DePompei, Kerr, & Congeni, 2003; McCrea, Hammeke, Olsen, Leo, & Guskiewicz, 2004; Register-Mihalik, Guskiewicz, Valovich McLeod, Linnan, Mueller, & Marshall, 2013; Valovich McLeod, Schwartz, & Bay, 2007). Furthermore, this lack of reporting may lead to what epidemiologists refer to as the “tip of the iceberg” phenomenon, where the incidence is far greater than the numbers represent. Still, researchers have attempted to estimate the incidence of concussions in sports, including specifically examining concussions in high school athletics.

In one of the first studies to explore concussions in high school athletics, Powell and Barber-Foss (1999) examined injuries at 235 high schools during the 1995-1997 school years. Injury rates were calculated by dividing the number of concussions by athletic exposures (AEs). An AE was defined as one athlete participating in one game or practice. Overall concussion rates, including both practice and competition situations, ranged from .02 concussions per 1,000 AEs (girls' volleyball) to .59 concussions per 1,000 AEs (football). Rates were higher during competition than in practice. Strikingly, the rate of concussion increased to 2.82 concussions per 1,000 AEs during game situations for football (Powell & Barber-Foss, 1999).

Gessel and colleagues (2007) and Marar and colleagues (2012) later assessed the incidence rate of SRC in high school sports by exploring the number of concussions per AE. The concussion injury rate reported by Gessel et al. was 2.3 concussions per 10,000 AEs, while Marar et al. found a rate of 2.5 concussions per 10,000 AEs. Similarly to Powell and Barber-Foss (1999), the concussion rate was lower in practice (1.1 concussions per 10,000 AEs) than in competition (5.3 – 6.4 concussions per 10,000 AEs). Out of all the concussions high school athletes incurred during the study period, the sport with the highest percentage of concussions was football (40.5 – 47.1%) (Gessel, et al., 2007; Marar, et al., 2012). Other sports that resulted in high rates of concussion were girls' soccer (8.2 – 21.5%), boys' soccer (15.4%), boys' wrestling (5.8%), and girls' basketball (5.5 – 9.5%) (Gessel, et al., 2007; Marar, et al., 2012). In exploring sex-comparable sports, those sports similarly played by both male and females, high school females had higher rates of concussion than their male counterparts (Gessel, et al., 2007; Marar, et al., 2012). The percentages of concussions accounted for in each sport may be slightly lower in the study by Marar and colleagues than reported by Gessel et al. because Gessel and colleagues explored only 9 high school sports, as compared to 20 sports.

A recent study exploring the change in concussion rates in high school athletics from the 2005-2006 school year until the 2011-2012 school year, demonstrated a significant increase in concussion rates from 0.23 to 0.51 (per 1,000 AEs) (Rosenthal, et al., 2014). Furthermore, 5 of the 9 sports studied (football, boys' basketball, boys' wrestling, boys' baseball, and girls' softball) demonstrated significant increases in concussion rates, while the other four sports supported an increasing trend, though results were not statistically significant (Rosenthal et al., 2014). Additionally, Rosenthal and colleagues found females had higher concussion rates than males in sex-comparable sports. However, as with previous research (Gessel, et al., 2007; Marar, et al., 2012), Rosenthal et al. found football to have the highest concussion rates (.49 per 1,000 AEs).

While it is difficult to ascertain the exact rate of SRC in high school athletics, it is apparent concussion is a prominent problem in high school sports. As the number of participants in high school sports continues to rise, the number of SRC will likewise continue to increase, as previous research suggests (Rosenthal, et al., 2014).

2.3 Definition of Concussion

There have been many proposed definitions of concussion that have been constantly revised due to the increasing knowledge about this injury. Further complicating matters is the use of colloquial and antiquated terms, such as "ding," or having one's "bell rung" (Guskiewicz, et al., 2004). The American Academy of Neurology (AAN) presents a broad definition for concussion, allowing for any trauma-induced alteration in mental state (Giza, et al., 2013). The definition from the AAN reads as follows: "concussion is recognized as a clinical syndrome of biomechanically induced alteration of brain function, typically affecting memory and orientation, which may involve LOC (Giza, et al, 2013, p. 2250)." Recently, the National Athletic Trainers'

Association in its position statement on the management of sport concussion defined concussion as, "a trauma induced alteration in mental status that may or may not involve loss of consciousness (Broglio, et al., 2014, p 246)." Finally, in its position statement, the American Medical Society for Sports Medicine (AMSSM) defines concussion as a "traumatically induced transient disturbance of brain function," that "involves a complex pathophysiological process (Harmon et al., 2013, p. 15)."

A more specific, and presumably more agreed upon definition of concussion is that devised from the 4th International Conference on Concussion in Sport in Zurich (McCrory, et al., 2013). In this consensus statement, concussion is defined as a "complex pathophysiological process affecting the brain, induced by biomechanical forces" (McCrory, et al., 2013, p. 250). The Zurich consensus statement purports there are several common factors among concussions that may be useful in defining the injury (McCrory, et al., 2013). First, concussions may be caused by either a direct blow to the head or an indirect hit elsewhere on the body, resulting in an impulsive force. Second, neurological symptoms following concussions typically begin rapidly and resolve spontaneously; however in some cases, symptoms may take longer to evolve. Third, concussions my result in neuropathological changes, but more frequently, clinical symptoms are a result of a functional disturbance. However, neuroimaging almost always reveals no structural abnormalities in a concussed athlete. Finally, concussions will produce an array of graded symptoms that may or may not include LOC. Resolution of these symptoms follows a typical sequence, but in some special cases, recovery may be prolonged (McCrory, et al., 2013).

2.4 Biomechanical Aspects of Concussion

For a concussion to occur, a shift in kinetic energy is required, specifically an acceleration and deceleration of the head and brain (Mihalik, 2012). Acceleration refers to a sudden speeding up of the head and brain. Typically this occurs when a stationary head is struck by a moving object, sending the head in motion (Park & Levy, 2008). Deceleration, respectively, is a slowing down of the head and brain (Mihalik, 2012), which often occurs when an athlete's moving head strikes a stationary object and comes to an abrupt stop (Park & Levy, 2008).

Acceleration can be further broken down into linear and rotational acceleration. Linear acceleration is when the brain moves in a straight line, while rotational acceleration occurs when the brain moves on an arc, deviating from the brain's center of gravity (Ommaya, Goldsmith, & Thibault, 2002; Mihalik, 2012). Rotational acceleration is thought to result in shearing of brain tissue, causing diffuse axonal injury (Ommaya, et al., 2002). While early research suggested the main cause for concussions and LOC was rotational acceleration (Ommaya & Gennarelli, 1974), more recent research surrounding concussive injuries suggests the cause is some combination of linear and rotational acceleration (Guskiewicz, Mihalik, Shankar, Marshall, Crowell, et al., 2007; Mihalik, Bell, Marshall, & Guskiewicz, 2007).

The acceleration and deceleration of the collision result in either an impact or an impulse. An impact is a direct blow to the head, while an impulse is a force experienced elsewhere on the body that sends the head into motion (Ommaya, et al., 2002; Mihalik, 2012). An example of an impact would be a helmet-to-helmet hit, where the opponent's helmet is directly striking the athlete's head (helmet). On the other hand, an example of an impulse would be a traditional tackle, where the opponent is stopping the athlete's body from being in motion while the head continues in motion, resulting in the head feeling the impulse mechanism. Frequently, the severity of the injury has been related to the acceleration of the head and brain, as well as the impact and impulse mechanisms (Mihalik, 2012).

Effectively measuring the head impacts that occur in football is critical to determine the biomechanical forces that cause SRC. To date, helmet sensor technology has been used to measure the type, magnitude, location, and frequency of head impact forces that occur in the sports of football and ice hockey (Mihalik, 2012). The Head Impact Telemetry System (HITS) is comprised of 6 single-axis accelerometers inserted into the spaces between the padding in football and ice hockey helmets (Mihalik, 2012). The placement of the accelerometers allows researchers to gain measurements of linear acceleration and rotational acceleration. The measurements are sent to a sideline controller instantly where they are time stamped and added to information on head impact biomechanics (Mihalik, 2012). This information allows researchers to look objectively at hits taken during practices and competition that may have resulted in a concussion. The HITS severity profile is a score comprised of linear acceleration, rotational acceleration, and impact duration, weighted by impact location (Guskiewicz & Mihalik, 2011).

Research exploring biomechanical aspects of concussions in high school football players suggests that offensive skills players (e.g., quarterbacks, running backs, and wide receivers) sustain the most concussions of any position, as these players sustained the greatest magnitude of linear acceleration (Broglio, Sosnoff, Shin, He, Alcaraz, & Zimmerman, 2009). In professional football players, concussions occurred with both linear and rotational acceleration; however the strongest correlation was with linear acceleration (Pellman, Viano, Tucker, Casson, & Waeckerle, 2003).

Recent research involving collegiate football players demonstrates that concussions are more likely to occur from top-of-the-head impacts (Guskiewicz & Mihalik, 2011). Furthermore, these top-of-the-head impacts may result in more postural instability (Guskiewicz & Mihalik, 2011). However, location of impact is not always predictive of acute clinical outcomes. This research exploring the biomechanics of SRC has also revealed that concussions can occur at a lower impact magnitude than previously thought; however, many athletes may experience a high number of impacts over a season, several with high impact magnitudes, and never receive a diagnosis of concussion (Guskiewicz & Mihalik, 2011). Also, while it was previously believed that rotational acceleration was more involved in concussive injuries, linear acceleration appears to be equally important (Guskiewicz & Mihalik, 2011). In summary, linear and rotational acceleration, impact magnitude, and impact location all seem to work in conjunction in concussive injuries, though the threshold for such injuries has yet to be determined.

Previous research suggests there may be a link between weaker neck muscles and the risk of concussive injury (Broglio, et al., 2009; Eckner, et al., 2014; Viano, Casson, & Pellman, 2007). Research exploring the biomechanics of concussion in high school football players found a greater rate of concussive injuries in high school athletes than collegiate athletes, results the researchers attribute in part to the weaker neck muscles of the high school players (Broglio, et al., 2009). Exploring this relationship in models of children, women, and men, it was demonstrated that as neck strength increased, the change in velocity after impact decreased, resulting in lower head displacement, which is linked to concussive injuries (Viano, et al., 2007). In contrast, however, some research has failed to identify any clear relationship between neck strength and concussive injuries (Mansell, Tierney, Sitler, Swanik, & Stearne, 2005; Mihalik, Guskiewicz, Marshall, Greenwald, Blackburn, & Cantu, 2011). Because research in this field of neck strength and its effect on SRC is still in its infancy, no clear relationship can be established at this point.

2.5 Pathophysiology of Concussion

After a concussive injury, a neurometabolic cascade occurs in the brain. The neurometabolic cascade is a combination of ionic shifts, altered metabolism, and changes in neurotransmission, and it results in neuronal dysfunction (Giza & Hovda, 2001). The neuronal dysfunction is transient in nature and therefore not representative of cell death. The ionic, metabolic, and physiologic events occur rapidly after injury (see Figure 1).

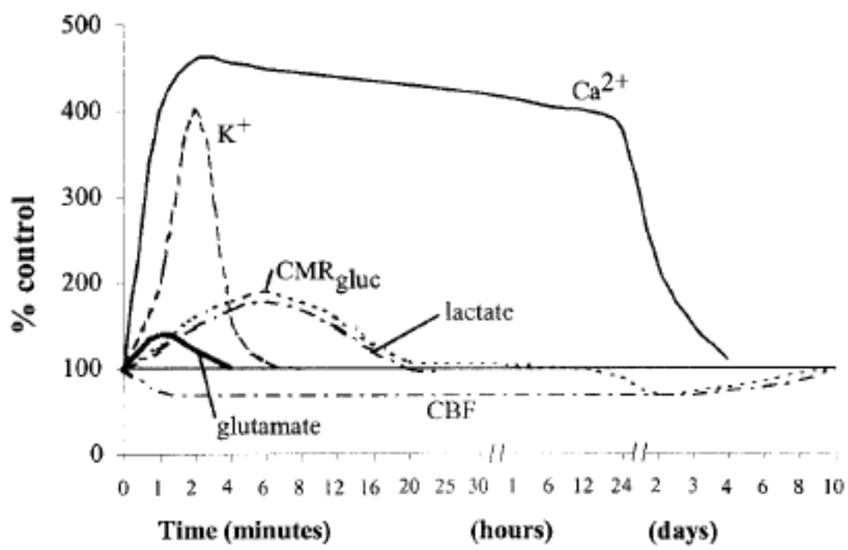

Figure 1. The neurometabolic cascade following experimental concussion. K^+, potassium; Ca^{2+}, calcium, CMRgluc, oxidative glucose metabolism; CBF, cerebral blood flow. From "The Neurometabolic Cascade of Concussion," by C. Giza and D. Hovda, 2001, *Journal of Athletic Training*, *36*, p. 229. Reprinted with permission.

Immediately following a concussion, there is a release of neurotransmitters and excitatory amino acids, including glutamate, which can activate receptors responsible for potassium (K^+) and calcium (CA^+) exiting and entering the cell, respectively (Figure 1). Once these receptors are activated, there is an influx of CA^+ into the cell and an efflux of K^+ out of the cell. Because the cell is always striving to achieve homeostasis, the sodium-potassium (NA^+-K^+) pump begins to work overtime, attempting to restore previous cellular potential. In order for the NA^+-K^+ pump to maintain this increased workload, it requires increasing amounts of adenosine triphosphate, which boosts glucose metabolism. At this time there is also a reduction in cerebral blood flow (CBF), potentially as low as 50% of normal blood flow.

Previous research involving induced traumatic brain injury in rats has demonstrated a reduction in both regional and total CBF (Yamakami & McIntosh, 1989; Yuan, Prough, Smith, & Dewitt, 1988). Yuan and colleagues demonstrated a heterogeneous decrease in CBF after brain injury in rats. Measuring CBF at 5 minutes, 15 minutes, 30 minutes, and one hour after injury Yuan, et al. demonstrated decreased CBF at each time point that worsened as time progressed. General CBF was significantly depressed at 1-hour post-injury at only 52% of baseline (Yuan, et al., 1988).

Similarly, Yamakami and McIntosh (1989) investigated the effects of fluid percussion injury of moderate severity in rats on CBF and found that up to one hour after injury, total CBF was significantly decreased. In fact, at 15 minutes after injury, CBF was only 48% of baseline; however, total CBF levels returned to near normal by 2 hours post-injury, at 81% of baseline. Interestingly, regional CBF, specifically where the injury had occurred, remained significantly depressed at 2 hours post-injury at only 49% of baseline (Yamakami & McIntosh, 1989).

As a result of the diminished CBF and the increased glucose metabolism, there is a disparity between glucose supply and demand resulting in a significant energy crisis (Giza & Hovda, 2001). After this stage of glucose hypermetabolism, the brain then enters a period of depressed metabolism. However, prolonged increases in CA^+ continue to worsen the energy crisis experienced in the brain. If the CA^+ increases persist and remain unchecked, neural connectivity may be impaired. Furthermore, cell death may occur as a result of CA^+ accumulations (Giza & Hovda, 2001).

Another component of the pathophysiology of a concussion is the generation of lactic acid as a result of accelerated glycolysis. As previously stated, following a concussion there is a state of glucose hypermetabolism. This hypermetabolism stimulates lactate production. Lactate metabolism is concurrently decreased, resulting in an accumulation of lactate. Increased lactate levels can result in neural dysfunction and may leave neurons more vulnerable (Giza & Hovda, 2001). Additionally, long-term deficits in memory and cognition are not uncommon following a concussive injury due to impairment in the hippocampus of long-term potentiation (Giza & Hovda, 2001).

2.6 Signs and Symptoms of Concussion

Athletes may present with many different symptoms after sustaining a concussion. Often the symptoms existing after a concussion will vary considerably between athletes (McCrory, et al., 2013). Typically, signs and symptoms are measured by self-report questionnaires, where the athlete will rate 20 or more symptoms on Likert scales (Kontos, Elbin, Schatz, Covassin, Henry, Pardini, & Collins, 2012). As a result of the different presentation of symptoms, researchers and clinicians have aggregated the possible symptoms into categories or clusters, which can be beneficial in the treatment and management of concussions (Kontos, et al., 2012).

The Post-Concussion Symptom Scale (PCSS) is a 22-item checklist, rated on a 7-point Likert scale designed to measure the severity of symptoms after a concussion (Lovell, et al., 2006). The symptoms range from headache and nausea to sensitivity to light and noise, and individuals are instructed to rate their symptoms over the past 2 days (see Table 1). Research has demonstrated the internal consistency reliability, as measured by Cronbach's alpha, to be strong, ranging from .88 to .94 in a sample of healthy high school and collegiate athletes (Lovell, et al., 2006). In concussed high school and collegiate athletes, the internal consistency continues to be strong, as Cronbach's alpha measured .93 in previous research (Lovell, et al., 2006). The most commonly reported symptoms following a concussion are headaches, fatigue, feeling slowed down, drowsiness, difficulty concentrating, feeling mentally foggy, and dizziness. Similarly, the least reported symptoms are nervousness, feeling more emotional, sadness, numbness or tingling, and vomiting (Lovell, et al., 2006).

Table 1.

The Post-Concussion Symptom Scale

Symptom	None	Mild		Moderate		Severe	
Headache	0	1	2	3	4	5	6
Nausea	0	1	2	3	4	5	6
Vomiting	0	1	2	3	4	5	6
Balance Problems	0	1	2	3	4	5	6
Dizziness	0	1	2	3	4	5	6
Fatigue	0	1	2	3	4	5	6
Trouble Falling Asleep	0	1	2	3	4	5	6
Sleeping More Than Usual	0	1	2	3	4	5	6
Sleeping Less Than Usual	0	1	2	3	4	5	6
Drowsiness	0	1	2	3	4	5	6
Sensitivity to Light	0	1	2	3	4	5	6
Sensitivity to Noise	0	1	2	3	4	5	6
Irritability	0	1	2	3	4	5	6
Sadness	0	1	2	3	4	5	6
Nervousness	0	1	2	3	4	5	6

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Table 1 (cont'd)

Symptom	None	Mild		Moderate		Severe	
Feeling More Emotional	0	1	2	3	4	5	6
Numbness or Tingling	0	1	2	3	4	5	6
Feeling Slowed Down	0	1	2	3	4	5	6
Feeling Mentally "Foggy"	0	1	2	3	4	5	6
Difficulty Concentrating	0	1	2	3	4	5	6
Difficulty Remembering	0	1	2	3	4	5	6
Visual Problems	0	1	2	3	4	5	6

From "Measurement of Symptoms Following Sports-Related Concussion: Reliability and Normative Data for the Post-Concussion Scale," by M. Lovell, G. Iverson, M. Collins, K. Podell, K. Johnston, D. Pardini, J. Pardini, J. Norwig, J. Maroon, 2006, *Applied Neuropsychology, 13*(3) p. 168. Reprinted with permission.

Kontos and colleagues (2012) recently revised the PCSS, including factor solutions for baseline and post-concussion symptoms. In a large sample of 30,455 healthy athletes (27,008 high school, 3,447 collegiate), baseline clusters were determined to be cognitive-sensory, sleep-arousal, vestibular-somatic, and affective, representing 49.1% of the variance in symptoms (Kontos, et al., 2012). These clusters were named for the predominating factor within each cluster. Female athletes demonstrated higher levels of the cognitive-sensory, sleep-arousal, vestibular-headache, and arousal factors at baseline than male athletes. The 1,438 post-concussion participants were made up of 944 high school athletes and 494 collegiate athletes. Exploratory factor analysis revealed 4 post-concussion factors that accounted for 58.3% of the symptom variance and were as follows: cognitive-fatigue-migraine, affective, somatic, and sleep-arousal (Kontos, et al., 2012). The cognitive-migraine-fatigue cluster includes headache, dizziness, fatigue, drowsiness, sensitivity to light/noise, feeling slowed downed, mentally foggy, and difficulty remembering/concentrating (Kontos, et al., 2012). The affective symptom cluster includes sadness, nervousness, and feeling more emotional (Kontos, et al., 2012). The somatic symptom cluster includes vomit and numbness/tingling (Kontos, et al., 2012). Finally, the sleep cluster includes trouble falling asleep and sleeping less than usual (Kontos, et al., 2012). In the post-concussion group, females reported higher levels of the affective factor than males.

Recent research suggests athletes' perceptions of recovery are heavily based upon symptoms, specifically somatic symptoms (e.g. headache, vomiting, and visual disturbances), rather than neurocognitive performance (Sandel, Lovell, Kegel, Collins, & Kontos, 2013). Sandel and colleagues explored perceived recovery from concussion in 101 athletes (62 male; 39 female), aged 12-18 years old (m = 14.75 years; SD = 1.76). All four symptom clusters (e.g., somatic, cognitive, neuropsychiatric, and sleep) were significantly, negatively correlated with perceived recovery. Furthermore, multiple regression analysis demonstrated while a combined model of symptoms and neurocognitive performance accounted for 58% of the variance in perceived recovery, a separate model of symptoms only accounted for 56% of the variance, with the somatic cluster of symptoms being a significant predictor in both models (Sandel, et al., 2013). The authors suggest utilizing a multidisciplinary approach to recovery management and return-to-play decisions is necessary.

Given the multitude of symptoms with which an athlete may present, symptom clusters can help practitioners and researchers manage concussions and make return-to-play decisions based on the most prominent cluster (Kontos, et al., 2012). Furthermore, research suggests females experience more symptoms post-concussion than males, which may better inform decisions during concussion recovery. Athletes tend to view these symptoms in direct relation to their perceived recovery, so it is important to use a multidisciplinary approach to recovery (Sandel, et al., 2013).

2.7 Management of Sport-Related Concussion

Grading scales and return-to-play guidelines. Although concussion grading scales have been abolished by all consensus and position statements (Broglio, et al., 2014; Giza, et al., 2013; Harmon, et al., 2013; McCrory, et al., 2013), it is still important to discuss them, as some clinicians continue to grade concussions. One of the most frequently referenced grading scales used in concussion management is that proposed by Cantu (1986). In the grading scale put forth by Cantu, the severity of concussion is determined based on LOC and duration of posttraumatic amnesia (PTA). A concussion is deemed “grade 1” if there is no LOC and PTA is under 30 minutes. A seemingly more severe “grade 2” concussion exists when either LOC is present and under 5 minutes, or PTA lasts between 30 minutes and 24 hours. Finally, the most severe “grade 3” concussion is given to those concussions where LOC is present and lasts above 5 minutes, or PTA is greater than 24 hours (Cantu, 1986). This scale has since been modified based on more current evidence, suggesting post-concussive symptoms should be utilized in evaluating the severity of a concussion. In the newer Cantu grading scale, grade 1 concussions also include those with post-concussive symptoms lasting less than 30 minutes or PTA less than 30 minutes. Grade 2 concussions are those concussions with signs and symptoms or PTA lasting between 30 minutes and 24 hours, and LOC lasting less than one minute. Finally, grade 3 concussions will have symptoms lasting longer than 7 days, as well as PTA remaining for over 24 hours or LOC lasting more than one minute (Cantu, 2001).

Presently, concussion grading scales are rarely used to determine return to play, and instead are strictly used for the purpose of medical record documentation after the injury has resolved (Broglio, et al., 2014). It is universally agreed upon that return to play should not occur before all symptoms have been resolved, both at rest and after exertion (Broglio, et al., 2014; Cantu, 1992; Giza, et al., 2013; Harmon, et al., 2013; McCrory, et al., 2013). Furthermore, all position and consensus statements agree that return to play should occur individually in a gradual, stepwise progression (Broglio, et al., 2014; Giza, et al., 2013; Harmon, et al., 2013; McCrory, et al., 2013). In a gradual, stepwise return to play, the individual should not progress to the next stage of rehabilitation until completely asymptomatic at the current stage. In the Zurich consensus statement, it is specifically noted that return to play should not occur on the same day of the concussive injury (McCrory, et al., 2013).

The gradual, stepwise return to play protocol should follow six basic steps (McCrory, et al., 2013). First, the athlete should not engage in any activity in order to fully recover. Once asymptomatic, the athlete may progress to the second rehabilitation stage, in which the athlete will engage in light aerobic activity, with the objective of increasing heart rate. If the athlete is able to complete the second stage with no symptoms returning, the athlete may progress into the third stage of recovery including sport-specific exercises, where the athlete is now incorporating movement into rehabilitation. The fourth stage of rehabilitation is non-contact training drills. In this stage, the main objective for the athlete is to exercise and increase coordination and the cognitive load. By the fifth stage of rehabilitation, the athlete will return to full-contact practice in order to restore confidence and assess functional skills. Finally, once the athlete has progressed through the first five stages of rehabilitation and is asymptomatic, the athlete may return to play, including competition (McCrory, et al., 2013). Each stage should stake approximately 24 hours, causing the entire protocol to last about a week. If at anytime the symptoms return, the athlete should return to the last asymptomatic stage and attempt to progress again after 24 hours (McCrory, et al., 2013).

While concussion grading scales are largely unused at this point, the Cantu (1992) scale remains the most frequently cited. When a grading scale is used, however, it is strictly for diagnostic and recording purposes, rather than for determining return to play. All grading scales suggest a gradual, stepwise return to play, determined on an individual basis.

Sport-related concussion consensus and position statements. While there are numerous position statements and consensus statements regarding SRC, the majority of these statements recommend a multifaceted approach to the diagnosis and management of a concussion. The AAN defines concussion as a "clinical syndrome of biomechanically induced alteration of brain function, typically affecting memory and orientation, which may involve LOC (Giza, et al., 2013, p. 2250)." In its position statement, the AAN recommends a comprehensive approach to the diagnosis of a suspected concussion, using a combination of symptom checklists, neuropsychological testing, and balance testing. However, the guidelines, while suggesting numerous diagnostic tests, do not suggest the best combination of tests to use. Furthermore, the AAN suggests previous history of concussion, posttraumatic headache, fatigue, fogginess, early amnesia and alteration in mental status, as well as younger age and level of play, are risk factors for prolonged post-concussion impairments (Giza, et al., 2013). In a change from the 1997 guidelines, the AAN has abandoned the use of a grading system for concussions, and instead, recommends more individualized treatment and recovery plans. Specific recommendations on return-to-play, as mentioned previously, are not discussed in depth in these guidelines. The AAN guidelines, however, specifically recommend a licensed health care provider with particular training in concussion should be consulted during recovery and when making return to play decisions, although details on what determines appropriate training in concussions are not given (Giza, et al, 2013).

Similarly, NATA has recently released a new position statement on the management of sport concussion. The NATA strongly recommends the use of proper terminology, deeming such terms as "bell ringer" and "ding" to be antiquated and inappropriate. Similar to the guidelines suggested by the AAN and the AMSSM, the NATA suggests possible risk factors and modifiers that may delay return to play, such as: age, concussion history, and the number, duration, and severity of concussive signs and symptoms. Furthermore, baseline neurocognitive testing and clinical examinations are recommended for all athletes in contact or collision sports (Broglio, et al., 2014). For the evaluation of a suspected concussion, the NATA recommends the use of a combination of neurocognitive testing, symptom checklists, and motor-control assessments.

Presumably, the most frequently referenced guidelines on the management of SRC are those developed at the 4th International Conference on Concussion in Sport in Zurich (McCrory, et al., 2013). The Zurich consensus statement asserts the majority of concussions (80-90%) are resolved within a short, 7-10 day time period. Concussions are typically diagnosed in the acute phase by the presence of clinical symptoms, physical signs, behavioral changes, cognitive impairments, and/or sleep disturbances. As mentioned in the previous guidelines (Giza, et al., 2013; Harmon, et al., 2013; Broglio, et al., 2014), the Zurich consensus statement emphasizes the importance of immediately removing any athlete suspected of a concussion from play, and evaluating the athlete (McCrory, et al., 2013). Again, the Zurich consensus statement acknowledges the utility of using a combination of neurocognitive testing with symptom scales and balance assessments.

All of the referenced consensus statements advocate for a multifaceted approach to concussion management, and stress the importance of removing an athlete from play immediately upon incurring a suspected concussion (Giza, et al., 2013; Harmon, et al., 2013; Broglio, et al., 2014; McCrory, et al., 2013). Additionally, while the consensus statements agree concussions may result in clinical and physical symptoms as well as cognitive impairments, there remains debate about the use of neurocognitive testing for diagnosis and management of SRC (Giza, et al., 2013; Harmon, et al., 2013; Broglio, et al., 2014; McCrory, et al., 2013).

Neurocognitive testing and sport-related concussion. While there is some debate as to the utility of neurocognitive testing in the management of SRC, the majority of position statements recommend its use in combination with symptom checklists and balance assessments (Broglio, et al., 2014; Harmon, et al., 2013; McCrory, et al., 2013). Moreover, because symptom presentation and recovery time is variable among athletes, it is important to assess all three areas for a more comprehensive understanding of recovery (Echemendia, et al., 2013; Grindel, Lovell, & Collins, 2001). In fact, some research at the high school level suggests resolution of signs and symptoms may occur before full cognitive recovery (McClincy, Lovell, Pardini, Collins, & Spore, 2006; Fazio, Lovell, Pardini, & Collins, 2007).

Previous studies have explored recovery from SRC with neurocognitive testing (McClincy, et al., 2006; Fazio, et al., 2007; Van Kampen, Lovell, Pardini, Collins, & Fu, 2006). McClincy and colleagues (2006) found neuropsychological assessments indicated cognitive deficits persisted at least until 14 days after the injury, while symptoms had returned to baseline standards by 7-10 days post-injury. Similarly, Fazio et al. (2007) found a group of asymptomatic concussed athletes continued to perform significantly poorer than a control group with no concussion. These findings suggest impairments in neurocognitive functioning may still be present even after the resolution of all signs and symptoms of a concussion (McClincy, et al., 2006; Fazio, et al., 2007).

Furthermore, Van Kampen and colleagues (2006) found the use of neurocognitive testing increased the likelihood of correctly identifying a concussed athlete compared to the use of symptom report alone. In a study testing high school and collegiate athletes 2 days post-injury, 64% of athletes demonstrated a significant increase in symptoms from baseline, while 83% of athletes performed significantly poorer on neurocognitive testing compared to baseline. Additionally, 93% of the athletes had either abnormal neurocognitive testing results or a significant increase in symptoms. These results again highlight the utility of neurocognitive testing in conjunction with other measures of recovery (Van Kampen, et al., 2006).

There also remains debate about the necessity of baseline testing. Recent studies have attempted to explore the utility of baseline testing compared to using standardized baseline population means (Echemendia, Bruce, Bailey, Sanders, Arnett, & Vargas, 2012; Schmidt, Register-Mihalik, Mihalik, Kerr, & Guskiewicz, 2012). Echemendia and colleagues examined the ability to determine cognitive change following SRC without baseline data. Utilizing the post-injury data alone and calculating reliable change data based on population means allotted a sensitivity between 80%-86% and a specificity between 95%-97%. Similarly, Schmidt et al. (2012) explored the use of normative data versus individualized baselines in calculating reliable change scores in neurocognitive performance post-concussion. While the baseline comparison method identified 2.6 times more impairments than the normative comparison method on RT, the normative comparison method identified 7.6 times more impairments for mathematical processing. These results suggests baseline testing may be unnecessary, as the majority of athletes who experience a clinically significant impairment in neurocognitive performance post-injury may be identified using post-injury information (Echemendia, et al., 2012; Schmidt, Register-Mihalik, Mihalik, Kerr, & Guskiewicz, 2012).

Because most research indicates symptom recovery may occur before cognitive recovery, a multifaceted approach is recommended when determining return-to-play, including the use of neurocognitive measures. While there remains debate on the necessity of baseline data, comparisons of post-injury neurocognitive data to population means may be useful in diagnosing and managing SRC. Given the range of symptom presentation, as well as the duration of recovery, a more comprehensive approach is most appropriate, potentially including measures of vestibular occulomotor sensitivity and memory.

2.8 Age Differences and Sport-Related Concussion

Second Impact Syndrome. First described by Schneider in 1973 and later referred to by Saunders and Harbaugh (1984) as "the second-impact syndrome of catastrophic head injury," it is now simply referred to as second-impact syndrome (SIS). In this syndrome, an athlete who is still experiencing post-concussion symptoms will return to play, suffering a second, often mild impact, resulting in death (Cantu, 1992; Cantu & Voy, 1995; Cantu, 1998; Cantu & Gean, 2010). SIS is most often seen in athletes under the age of 18 (Cantu & Gean, 2010).

Cantu and colleagues have described the pathophysiology of SIS, where hyperemic brain swelling within the cranium leads to a rapid increase in intracranial pressure. From there, herniation of the temporal lobes and the cerebellar tonsils occurs, along with brainstem compression. At the onset of SIS, the athlete will very rarely lose consciousness, but instead will remain on his/her feet, often completing the play and walking off the field under his/her own power, although the athlete may seem disoriented. However, the time period from the impact to brainstem failure is often rapid, between 2 and 5 minutes. After brain stem failure occurs, typically a loss of eye movement and respiratory failure will occur (Cantu, 1992; Cantu & Voy, 1995; Cantu, 1998; Cantu & Gean, 2010).

Age-related pathophysiological differences. There may be developmental periods in which the brain is more sensitive to injury; specifically brain injury in children results in higher rates of mortality, presumably because of the higher incidence of cerebral edema (Giza & Hovda, 2001). It is, however, difficult to ascertain to what extent brain injury may affect the developing brain. Specifically, overt signs of any neurologic dysfunction may not be present at a particular developmental stage; any delay in development may only be seen at a later time (Giza & Hovda, 2001). The best experimental example of possible developmental plasticity after brain injury comes in the form of rats exposed to enriched environments versus typical laboratory rearing rats. Rats that are reared in an enriched environment will demonstrate increases in cortical thickness, larger neurons, more glia, a greater number of synapses, and enhanced dendritic branching compared to those rats that are not reared in the same environment. However, rats that suffer a brain injury during the developmental periods will not show these same increases in cortical thickness and cognitive performances in enriched environments, thereby illustrating the potential long-term pathophysiological effects of brain injury on the developing brain (Giza & Hovda, 2001).

Age-related symptom and neurocognitive performance differences. Many studies have suggested there may be differences in the presence and duration of post-concussion symptoms between age groups (Covassin, et al., 2012b; Cantu, Guskiewicz, Register-Mihalik, 2010; Field, Collins, Lovell, & Maroon, 2003). In a study exploring age differences in post-concussion symptoms, Covassin et al., evaluated high school and collegiate athletes (779 high school; 837 college). Results suggested high school athletes experienced a greater number of baseline somatic-migraine symptoms than collegiate athletes. However, college athletes reported experiencing more emotional and sleep symptoms at baseline than the high school athletes (Covassin, et al., 2012b).

Cantu and colleagues (2010) and Field and colleagues (2003) found differences in the duration of symptoms between high school and collegiate athletes after sustaining a concussion. Both studies demonstrated prolonged symptomology in the high school athletes compared to the college athletes (Cantu, et al., 2010; Field, et al., 2003). Furthermore, memory dysfunction persisted longer in the high school athletes than in the college athletes (Field, et al., 2003).

In comparing research exploring recovery from concussion in high school athletes to collegiate athletes, it is possible high school athletes may have a longer recovery period. Research by McCrea and colleagues (2003) exploring post concussive symptoms, cognitive performance, and postural stability following a concussion in collegiate football players suggests the majority of athletes will be cleared for competition by 7 days post injury. The majority of athletes had returned to preseason baseline levels of cognitive performance by day 7 and to preseason postural stability by day 5 (McCrea, et al., 2003). Lovell et al. (2003) similarly explored recovery patterns from concussion in high school athletes. The athletes were administered ImPACT during a preseason evaluation, and again 3 times post-injury at 36 hours, and 4 and 7 days. Contrary to the collegiate athletes studied by McCrea and colleagues, cognitive recovery had not been reached by day 7 in the high school athletes, whereas symptoms resolution had occurred by day 4 (Lovell, et al., 2003).

Conversely, some studies have found no age-related differences in symptom presence and duration (Lee, Odom, Zuckerman, Solomon, & Sills, 2013; Covassin, et al., 2012a). Covassin and colleagues and Lee et al., examined symptom recovery after SRC in high school and collegiate athletes. The findings suggested no significant difference between number and severity of post-concussion symptoms (Lee, et al., 2013; Covassin, et al., 2012a). Furthermore, there was no significant difference between the times to return to baseline between the groups (Lee, et al., 2013; Covassin, et al., 2012a), suggesting no age-related difference in duration of post-concussion symptoms.

Age was not found to be associated with recovery time in a study done by Meehan and colleagues (2013). One hundred and eighty-two patients, ranging in age from 7.6 to 26.7 years (average = 15.2 years; SD = 3.04 years) completed ImPACT, Balance Error Scoring System, and the Post-concussion Symptom Scale after sustaining a concussion (Meehan, Mannix, Stracciolini, Elbin, & Collins, 2013). Meehan et al. explored age, posttraumatic amnesia, postural stability, cognitive performance, and total symptom scores for possible associations to a prolonged recovery marked by symptoms persisting past 28 days post-injury. Interestingly, a younger age was not associated with a longer duration of symptoms (Meehan, et al., 2013). These results imply that age does not play a role in the recovery time following a concussion.

While some research has found differences in symptoms present as well as duration of recovery following a SRC between high school and collegiate athletes (Covassin, et al., 2012b; Cantu, et al., 2010; Field, et al., 2003), other research has failed to demonstrate these effects (Lee, et al., 2013; Covassin, et al., 2012a). As such, there remains some debate as to the age-related effects on concussion symptoms and neurocognitive performance.

2.9 Cumulative Effects of Concussion

Do athletes with a history of concussion have a higher risk for subsequent concussion? Early research by Gerberich and colleagues (1983) and Guskiewicz et al. (2000; 2003) suggested that athletes, specifically football players, who had sustained a concussion were

3 to 4 times more likely to have a second concussion than those players with no previous history of a concussion. Furthermore, those players who had sustained a previous concussion within the last year, reported more symptoms, and specifically experienced LOC and amnesia at a greater rate, than those players who had not incurred a previous concussion within the last year (Gerberich, et al., 1983; Guskiewicz, et al., 2000). These findings suggest not only are those athletes with a history of concussion at a greater risk of incurring a second concussion, but the second concussion is often of greater severity (Guskiewicz, et al., 2000).

Recent research has begun exploring the possibility of a reduced threshold for subsequent concussive injuries. A dose-response has been noted in the amount of previous concussions and the risk of subsequent concussive injuries. Athletes with a history of one or 2 previous concussion(s) were 1.5 and 2.8 times more likely to incur a subsequent concussion than athletes with no previous concussion. Furthermore, those athletes with a history of 3 or more concussions were 3.4 times more likely to sustain another concussion than those athletes with no history of concussion (Guskiewicz, et al., 2003). These results clearly indicate a dose-response relationship between the number of previous concussions and the likelihood of sustaining an incident concussion; in fact, many current concussion guidelines strongly consider concussion history when making return-to-play suggestions.

While the majority of studies exploring the possibility of an increased risk for subsequent concussions have been retrospective in nature, Zemper (2003) conducted a prospective study at the high school and collegiate level in football. The results indicated a relative risk of concussion of 6.6 (CI = 5.0-8.8) times greater for those athletes with a history (within the last 5 years) of concussion, compared to those athletes with no history, at the high school level. Similarly, the relative risk for sustaining a concussion at the collegiate level for those athletes with a history of concussion was 5.8 (CI = 4.3-6.6) times greater than for those athletes with no prior concussion history. Overall, combining high school and collegiate participants, the relative risk for sustaining a concussion was 5.8 (CI = 4.8-6.8) greater in those athletes who sustained a previous concussion in the last 5 years (Zemper, 2003).

Albright and colleagues (1985) were among the first to explore head and neck injury patterns in college football. Three hundred and forty-two football players were included in an 8-year study after undergoing a physical examination before their freshman seasons, as well as documenting past medical history. Those athletes who sustained multiple concussions while playing college football missed on average 2.31 days for the initial concussion and 4.89 days for the subsequent concussions (Albright, McAuley, Martin, Crowley, & Foster, 1985). The results of the study indicated that while repeat head injuries are not any more likely, when they do occur, they are typically more severe, resulting in a longer loss of playing time (Albright, et al., 1985).

Further illuminating the increased risk for more severe subsequent concussions, Collins, et al. (2002), explored the cumulative effects of concussion. Those athletes who had a history of 3 or more previous concussions were significantly more likely to experience LOC, anterograde amnesia, and confusion. Furthermore, those athletes who had a history of 3 or more concussions were 9.3 times more likely to experience 3 or 4 on-field markers of injury severity after a subsequent concussion (Collins, et al., 2002).

While previous research seems to suggest the relative risk of incurring a concussion is higher in those athletes who have previously sustained a concussion (Gerberich, et al., 1983; Guskiewicz, et al., 2000; Guskiewicz, et al., 2003; Zemper, 2003), some researchers question the methodology of these studies (McCrory, et al., 2001). McCrory and colleagues brought forth the observation that previous concussions may not be the contributing factor to increasing a player's relative risk of concussion, but rather the style of play the athlete employs. In fact, Gerberich et al. found an increased risk for LOC, loss of awareness, and other concussive symptoms for those players who utilized illegal techniques such as butt-blocking and face-tackling. Additionally, McCrory et al. suggest the increased relative risk may also be attributed to the number of games played, thus the likelihood of incurring a second concussion is increased by the more games the athlete plays, not by previous concussions. Zemper addresses this particular point however, as the relative risk for sustaining a second concussion was found to be higher in high school athletes than collegiate athletes. Many studies have suggested that whether or not the risk for concussion is higher in those who have a history of previous concussion versus those with no history, the subsequent concussions are typically more severe and require a longer recovery period (Albright, et al., 1985; Collins, et al., 2002).

Do athletes with a history of concussion take longer to recover from subsequent concussion? The symptoms following a concussion during the acute phase have shown to be more prominent for those athletes with a history of concussion (Collins, et al., 2002). Collins et al. examined the presence of on-field concussive symptoms in athletes with no history of concussion, compared to those with a history of 3 or more concussions. Those athletes with a history of concussion were significantly more likely to present with on-field LOC, anterograde amnesia, and confusion after a concussion, than those athletes with no prior concussion history. More specifically, athletes with previous concussions were 6.7 times more likely to experience LOC. Furthermore, while only 9.4% of players with no previous concussion experienced prolonged post-injury mental status changes after the injury, 31.6% of players with a history of concussion demonstrated prolonged mental status change after the subsequent concussion.

Mental status change was a variable derived by including confusion, anterograde amnesia, and/or retrograde amnesia that occurred for longer than 5 minutes post-injury. When looking primarily at 4 on-field injury severity markers (e.g., LOC, anterograde amnesia, retrograde amnesia, and confusion), those players with a history of 3 or more concussions were 9.3 times more likely to experience 3 or 4 of these severity markers compared to those athletes with no history of concussion (Collins, et al., 2002). The results from Collins and colleagues suggest those athletes with a self-report history of 3 or more concussions are at an increased susceptibility to the acute effects of subsequent concussions.

Some research has explored recovery time following concussive injuries for those athletes with a history of concussion, compared to those without (Covassin, et al., 2013; Eisenberg, et al., 2013; Guskiewicz, et al., 2003; Covassin, et al., 2008). In the previously described study by Guskiewicz et al. (2003), symptom recovery was more gradual for those athletes with a history of multiple concussions. A striking comparison between those athletes with no previous concussions and those with 3 or more previous concussions shows prolonged recovery occurring in 7.4% of athletes versus 30.0% of athletes, respectively (Guskiewicz, et al., 2003).

Research has demonstrated prolonged impairment on neurocognitive measures for those athletes with a history of multiple concussions (Covassin, et al., 2013; Covassin, et al., 2008), as well as a higher report of post-concussive symptoms (Covassin, et al., 2013; Eisenberg, et al., 2013). Covassin and colleagues demonstrated high school and collegiate athletes with a history of 3 or more concussions were shown to be impaired on verbal memory and RT longer that athletes with 2 previous concussions, who were impaired longer than athletes with only one previous concussion (Covassin, et al., 2013; Covassin, et al., 2008). Furthermore, those athletes with 3 or more concussions continued to report high symptoms in the migraine-cognitive-fatigue cluster at 8 days post-injury, while all other groups had returned to baseline by this time point (Covassin, et al., 2013). Eisenberg and colleagues found pediatric patients who had sustained a previous concussion within the last year had nearly 3 times the median duration of symptoms compared to those who had no previous concussion history and those who had sustained a concussion over one year prior. Furthermore, those patients with a history of 2 or more concussions, had more than double the median symptom duration than those patients with no history or only one previous concussion. (Eisenberg, et al., 2013). These findings suggest individuals with a history of multiple concussions are at an increased risk for longer symptom duration and prolonged recovery.

In a study attempting to examine the recovery from concussion, Slobounov et al. (2007) used a virtual reality system measuring visual-kinesthetic integration recovery in collegiate athletes after sustaining a concussion. Nine athletes who experienced 2 concussions within one year were tested using this virtual reality system after each concussion. All of the athletes had been clinically cleared to return to play by day 10 post-injury based on neuropsychological assessments (Slobounov, et al., 2007). The results indicate the rate of recovery, as evident by the presence of visual-kinesthetic disintegration, was significantly slower in the athletes after the second concussion compared to the first concussion. Additionally, the visual-kinesthetic disintegration was noted at 30 days post-injury after the second concussion, where it was predominantly resolved by day 17 after the first concussion (Slobounov, et al., 2007). Despite the small sample size, these results indicate that recovery is significantly slower after a second concussion compared to the first concussion.

Many research studies have attempted to explore the cumulative effects of concussion by the recovery rate following subsequent concussions compared to athletes who have sustained their first concussions. The majority of these studies suggest recovery rate is slower for athletes who are returning after a subsequent concussion versus those athletes who have incurred their first concussions (Collins, et al., 2002; Covassin, et al., 2013; Eisenberg, et al., 2013; Guskiewicz, et al., 2003; Covassin, et al., 2008; Slobounov, et al., 2007). Furthermore, some research indicates these deficiencies in recovery time may not be noted simply through a clinical examination, or even neuropsychological testing (Slobounov, et al., 2007), indicating a more broad evaluation must be considered when making decisions on return to play.

Are there any cumulative, or long-term, neurocognitive effects associated with a history of multiple concussions? Current research is inconclusive regarding whether or not athletes with a history of concussions will continue to exhibit prolonged neurocognitive effects. Some research suggests that athletes with a history of multiple concussions continue to perform significantly worse on neurocognitive measures than those athletes who have no history of previous concussions (Covassin, et al., 2010; Iverson, et al., 2012; Iverson, et al., 2004; Master, et al., 1999; Moser & Schatz, 2002; Moser, et al., 2005; Master, Kessels, Lezak, & Troost, 2010; Schatz, et al., 2011; Guskiewicz, et al., 2005). Conversely, some studies have not found a significant difference in neurocognitive performance between those athletes with a history of concussions and those with no previous concussions (Broglio, et al., 2006; Bruce & Echemendia, 2009; Collie, McCrory, & Makdissi, 2006; Iverson, et al., 2006; Macciocchi, et al., 2001).

Poorer performance on verbal memory tasks has been noted at baseline in athletes with a history of 2 or more previous concussions compared to athletes with no history of concussion (Covassin, et al., 2010; Iverson, et al., 2012; Iverson, et al., 2004). Additionally, visual memory performance has been noted as significantly worse in those athletes with a history of 3 or more concussions compared to those athletes with no previous concussion (Covassin, et al., 2010; Iverson, et al., 2004). Similar results were demonstrated by Master et al. (2010), who found the number of previous concussions in professional soccer players to be inversely related to multiple neurocognitive measures, indicating a dose-response relationship between the number of concussions and sustained attention and visuoperceptual processing.

Moser and colleagues (2005) further demonstrated the trend of neurocognitive deficits following multiple concussions in high school athletes. Those athletes with a history of 2 or more concussions who were, at the time of the assessment, symptom-free, performed equally poor on cognitive tasks compared to those athletes who have sustained a concussion within the last week. Results mean that although these athletes are not demonstrating any physical, medical, or cognitive difficulties relating to a concussion, they are indistinguishable from those athletes who recently sustained a concussion. Furthermore, academic grade point average was found to be significantly lower for athletes with a history of 2 or more concussions compared to those with no history of concussion (Moser, et al., 2005).

Furthermore, previous research demonstrated athletes with a history of multiple concussions reported more symptoms at baseline than those athletes who had no concussion history (Iverson, et al., 2004; Schatz, et al., 2011). These differences between the athletes with a history of three or more concussions and the athletes with no history of concussion continued post-injury, as those athletes with a history of concussion were more likely to experience worse on-field severity markers of injury, such as post-traumatic amnesia and mental status disturbance (Iverson, et al., 2004). Schatz and colleagues indicated that those athletes with a history of two or more concussions reported higher ratings of headaches, balance problems, and dizziness than those athletes with no history or concussion and those athletes with a history of only one previous concussion. Additionally, nausea and fatigue were both rated significantly higher by those athletes with a history of two concussions compared to those athletes with no history of concussion. Furthermore, when examining the symptoms based on symptom clusters, athletes who had a history of two or more concussions reported higher ratings of physical symptoms than those athletes with no history of concussion, or only one previous concussion (Schatz, et al., 2011).

Guskiewicz et al. (2005) explored the possibility of cumulative, long-term effects of concussion in retired professional football players. By surveying retired players, Guskiewicz and colleagues attempted to attain information regarding mild cognitive impairment and Alzheimer's disease. The results of this survey indicated a relationship between recurrent concussions (three or more) and mild cognitive impairment, as well as severe memory problems, both self-report and spouse-report (Guskiewicz, et al., 2005). Specifically, those athletes who had a history of three or more concussions had a fivefold prevalence of mild cognitive impairment and a threefold prevalence of reported significant memory problems. These findings indicate that a history of multiple concussions may be associated with late life cognitive impairments.

In contrast, other research has demonstrated that among high school and university athletes, there was no difference in verbal memory, visual memory, RT, processing speed, and post-concussion symptoms at baseline for those athletes with a history of one or 2 previous concussions compared to those athletes with no history of concussion (Iverson, et al., 2006; Macciocchi, et al., 2001; Broglio, et al., 2006). Furthermore, players who sustained two previous concussions showed no significant difference in the amount of symptoms after the first concussion compared to the second concussion (Macciocchi, et al., 2001). Collie and colleagues

(2006) found similar results with elite Australian-rules football players. No significant differences were found between concussion history groups (e.g., no concussion, one concussion, two concussions, three concussions, four or more concussions) on tasks assessing motor function, decision making, attention, learning, and memory at baseline (Collie, et al., 2006).

Similarly, Bruce and Echemendia (2009) examined the association between concussion history and neurocognitive performance across three studies. The first study examined ImPACT composite scores across concussion groups and found no significant differences on cognitive performance between concussion history groups (Bruce & Echemendia, 2009). The follow-up study, utilized the Pennsylvania State University Concussion Battery, a traditional paper-and-pencil test. Results again suggest no significant differences in cognitive performance based on concussion history on traditional paper and pencil test neuropsychological tests. Finally, Bruce and Echemendia explored any differences in neurocognitive performance based on self-report concussion history on both the computerized (ImPACT) and traditional paper and pencil (Pennsylvania State University Concussion Battery) neuropsychological assessments. Again, no significant differences between athletes with no concussion, one concussion, or 2 or more concussions were found on either ImPACT or the Pennsylvania State University Concussion Battery (Bruce & Echemendia, 2009).

Currently, the literature remains indecisive and unclear. Many studies have demonstrated a dose-response effect from the number of concussions on neurocognitive performance (Covassin, et al., 2010; Iverson, et al., 2012; Iverson, et al., 2004; Master, et al., 1999; Moser & Schatz, 2002; Moser, et al., 2005; Master, et al., 2010); however, many studies have failed to reveal any significant differences between those with and without a history of concussion on neurocognitive performance and symptom presentation, both at baseline and post-injury

(Broglio, et al., 2006; Bruce & Echemendia, 2009; Collie, et al., 2006; Iverson, et al., 2006; Macciocchi, et al., 2001). One potential limitation with these studies is the lack of consistency with regards to which neuropsychological assessment is used. While many of the studies rely on utilizing ImPACT; Headminder CRI and CogSport are also used, as well as tasks such as the Trail Making Test and the Symbol Digit Test. Furthermore; many of the studies fail to explain the time since the last concussion, the time between subsequent concussions, and the severity of all concussions. Additionally, all of the studies rely on self-report of concussion history, which, while the most practical methodology, may not be the most reliant. While the results of studies exploring the cumulative effect of concussions continue to be varied, more research must be conducted exploring the possibility of neurocognitive effects after multiple concussions.

Are there any cumulative, or long-term, physiological changes associated with a history of multiple concussions? More recent research is beginning to explore the possible long-term effects of multiple concussions at a cellular level (Gaetz, Goodman, & Weinberg, 2000; De Beaumont, Brisson, Lassonde, & Jolicoeur, 2007; Thériault, De Beaumont, Tremblay, Lossonde, & Jolicoeur, 2011). Gaetz and colleagues explored the possible link between multiple concussions and a reduction in cognitive event-related potentials (ERP). Working with 271 junior hockey players who were not suffering from a recent concussion, Gaetz et al. utilized a self-report of symptoms and measured the N2/P3 paradigm and the contingent negative variation (CNV) paradigm. The N2/P3 response attempts to measure attention, stimulus evaluation, and the transfer of information to consciousness and memory systems (Gaetz, et al., 2000). The CNV is related to the processing of a warning stimulus and the response and preparation to a response stimulus (Gaetz, et al., 2000). All participants were at least 6 months out from their most recent concussion, with the average time being 13.2 months in the group with 3 or more concussions.

The findings demonstrated longer P3 latencies in those athletes who had a history of 3 or more previous concussions. P3 latency is particularly thought to be involved in stimulus evaluation and categorization, transfer of information to memory, and stimulus saliency. Furthermore, the latency of the P3 response was significantly correlated with higher reports of memory difficulties from the symptom questionnaire (Gaetz, et al., 2000). These findings indicate a history of multiple concussions, specifically 3 or more concussions, may be related to electrophysiological changes.

Similar findings were demonstrated by De Beaumont and colleagues (2007). Participants were 51 Canadian university football players, divided into groups based on concussion history (no previous concussion, one previous concussion, 2 or more previous concussions). Neuropsychological assessments as well as the Post-Concussion Symptom Scale were obtained for each of the subjects, and no differences were found across groups. The P3 amplitude was found to be significantly suppressed in the multi-concussed athletes when compared to those athletes who had no history of concussion or only one previous concussion (De Beaumont, et al., 2007). Furthermore, as those who had sustained multiple concussions were, on average, significantly more removed from their most recent injuries, time since injury was then entered as a covariate. The differences in the amplitude of the P3 component were still significant, even after accounting for time elapsed since the injury (De Beaumont, et al., 2007). Again, these findings indicated that even in athletes who are asymptomatic, a history of multiple concussions could have lasting electrophysiological effects, despite no significant neuropsychological deficiencies.

Utilizing fMRI data, Elbin, et al. (2012) examined the possible compensatory effect in the brain on working memory tasks. Fourteen previously concussed high school and collegiate athletes (2 or more previous concussions) were matched with 14 high school and collegiate athletes with no history of concussion. Those athletes in the previously concussed group had been asymptomatic for on average 9 months (SD = 6.67). Athletes completed the N-back working memory task during an fMRI. The regions of the brain activated by the concussed group were the same regions the control group activated, showing no compensatory changes in brain activation. These data highlight neurophysiological recovery following concussion (Elbin, et al., 2012).

While research exploring physiological changes in the brain following concussion is still in its infancy, some studies have demonstrated reduced P3 amplitude in athletes with a history of multiple concussions (Gaetz, et al., 2000; De Beaumont, et al., 2007), suggesting prolonged effects of concussion, specifically in the transfer of information to memory. However, fMRI data found athletes with a history of concussion utilize the same brain regions as a control group, suggesting that although there may be some long-term physiological effects of concussion, the brain does not demonstrate a compensatory effect (Elbin, et al., 2012).

2.10 Measurement of Physical Activity

Physical activity (PA) is any bodily movement that results in energy expenditure (Caspersen, Powell, & Christenson, 1985). Measuring PA can be difficult, and while direct observation of the activity is typically considered one of the gold standard assessments of PA measurement in research (Sirard & Pate, 2001), another approach may be more suited to the research question at hand. There are 3 different types of measures of PA in children and adolescents: primary measures (e.g., direct observation, doubly labeled water, indirect calorimetry), secondary measures (e.g., heart rate, pedometers, accelerometers), and subjective measures (e.g., self-report, interview, proxy-report, diary) (Sirard & Pate, 2001).

Direct observation of PA is considered the most appropriate criterion for measuring PA in young children (Sirard & Pate, 2001). There are multiple direct observation techniques that may be employed based on the time spent observing an individual (ranging from 3 seconds to one minute), the number of categories being observed, and the conditions under which the individual is being observed (e.g., physical education class, free play). While direct observation is considered the gold standard to which other measures of PA are compared, there are drawbacks to direct observation. There is a relatively high burden placed on the experimenter as well as a potential for a change in the participants' activity due to being observed (Sirard & Pate, 2001).

Secondary measures include objective techniques such as accelerometers, pedometers, and heart rate monitors. Heart rate monitors estimate PA based on the linear relationship between heart rate and oxygen consumption; however, this relationship is not as strong in the lower end of the PA spectrum, as heart rate can be affected by things other than bodily movement in sedentary or light activities (Sirard & Pate, 2001). Motion sensors such as pedometers and accelerometers are also used to measure PA. Pedometers measure PA by estimating the number of steps taken or the mileage walked. Pedometers have been demonstrated to be reliable and appropriate for large population studies, as they are inexpensive, reusable, and objective (Sirard & Pate, 2001). However, pedometers fail to measure the type and intensity of an activity. Accelerometers measure PA by attempting to measure accelerations in body movement. Accelerometers allow for a more specific measure of intensity of activity. Like pedometers, they are reusable, objective, and nonreactive. Depending on the model, accelerometers measure accelerations on a single plane or 3-dimensional plane, allowing for a more accurate assessment of PA. Because accelerometers are often worn on the hip, measurements of activities with little torso movement are often limited (Sirard & Pate, 2001). Objective measures of PA are beneficial for a variety of reasons. Objective measures avoid any bias that may arise from self-report or proxy-report, they provide a quantifiable measure of PA, which allows for exploration into possible dose-responses of PA, and they can highlight any discrepancies between objective and subjective measures (Reilly, Penpraze, Hislop, Davies, Grant, & Paton, 2008).

The final category of measures of PA is subjective techniques. These techniques include self-report questionnaires, interviewer-administered questionnaires, proxy-report questionnaires, and diaries. Self-report techniques are relatively inexpensive and typically conducive for large numbers or respondents. Furthermore, there is low burden on both the participant and the investigator in collecting self-report data. The greatest limitation with self-report techniques is the inherent subjectivity. Furthermore, the use of subjective techniques has a risk of recall errors and deliberate misrepresentations. Additionally, self-report questionnaires do not estimate many non-vigorous activities, which could limit their ability to accurately measure PA (Ara, Aparicio-Ugarriza, Morales-Barco, Nascimento de Souza, Mata, & Gonzalez-Gross, 2015). Correlations between subjective measures and primary or secondary measures of PA have varied widely (0.10 to 0.88) (Sirard and Pate, 2001). Furthermore, some previous research has found unfit participants may overestimate the time spent in moderate to vigorous PA when utilizing a self-report questionnaire (Shook, et al., 2015). Notably however, the agreement between self-report questionnaires and pedometers and accelerometers has been demonstrated to be relatively high in an adolescent population. Weston et al. (1997) demonstrated the Previous Day Physical Activity Recall to be positively associated with a pedometer ($r = 0.77$) and an accelerometer ($r = 0.88$) in a group of high school students. This high correlation, however, is most surely due in part to the limited time frame in which PA was reported.

The most appropriate means of assessing PA will depend on the situation. In larger sample sizes where criterion measures may not be feasible, the use of secondary measurements such as accelerometers, pedometers, and heart rate monitors may be an appropriate measure. In even greater sample sizes where it would be cost prohibitive to use electronic means, subjective techniques such as surveys may be beneficial. However, surveys should not be used under the age of 10 and are best when the recall time is short (Sirard and Pate, 2001).

2.11 Physical Activity and Cognition

Research indicates that physical activity has a direct relationship with cognitive function. In fact, many meta-analyses have been conducted on the association between both acute and chronic physical activity and improvements in cognitive function (Colcombe & Kramer, 2003; Sibley & Etnier, 2003; Smith et al., 2010; Fedewa & Ahn, 2011). These meta-analyses have been completed across the lifespan, investigating the effects of physical activity on both children's and adults' cognition.

Colcombe and Kramer (2003) conducted a meta-analysis on the effects of fitness on cognitive function in older adults, while Smith et al. (2010) conducted another meta-analysis on the effects of exercise and cognitive performance on young adults. Results from Colcombe and Kramer (2003) demonstrate that exercise intervention groups improved significantly more than the control groups. Utilizing point estimates for effect size on all cognitive tasks, control groups were found to be 0.164, whereas the exercise groups' point estimate effect size was 0.478. While both values demonstrate a significant effect, the control groups' improvement was about 1/8 of a standard deviation and the exercise groups' improvement was almost 1/2 standard deviation. With regards to young adults, modest improvements were demonstrated in attention and processing speed ($g = 0.158$), executive function ($g = 0.123$), and memory ($g = 0.128$), but the effects on working memory were not significant and were less consistent (Smith, et al., 2010). Results of these meta-analyses indicate regardless of the specific cognitive task, the training method, or the participants' characteristics, aerobic fitness training can increase cognitive performance in adults (Colcombe & Kramer, 2003; Smith, et al., 2010).

Similar meta-analyses have been done on the effects of physical activity on cognition in children. Sibley and Etnier (2003) conducted a meta-analysis in which the overall effect size for cognition was 0.32. When examining those studies that utilized an experimental design, the experimental groups had a significantly larger average effect size (ES = 0.52; SD = 0.47) than the control groups (ES = 0.12; SD = 0.39). Two results are of particular interest from this meta-analysis. First, the significant overall effect size of 0.32 indicates physical activity in children has a positive effect on cognition. Second, those studies that used stronger designs (e.g., experimental design) yielded a higher effect size, supporting the possibility that physical activity may cause improvements in cognition, however, more research must be conducted with true experimental design (Sibley & Etnier, 2003).

More recently, Hill and colleagues (2011) explored the effect of exercise on cognitive test performance in children between the ages of 8 and 12 years (m = 9 years 8 months; SD = 1 year 2 months). The children were divided into 2 groups; one group received the intervention for one week, followed by no intervention for a week, while the other group received the intervention the second week, after a week of no exercise intervention (Hill, Williams, Aucott, Thomson, & Mon-Williams, 2011). The cognitive test battery used a series of tasks, each given on a specific day. The results demonstrated an increase in overall performance on the cognitive test battery in the group who received the intervention the second week, greater than what would be expected from practice effects (Hill, et al., 2011). These findings from Hill and colleagues suggest there may be a positive effect of exercise on cognitive performance in children.

Fisher et al. (2011) investigated the effects of a 10-week physical activity intervention on cognition. Participants were 64 children (age = 6.2 years; SD =0.3 years) recruited from 6 primary schools. The schools were placed either into a control physical education group or an intervention physical education group. The intervention program consisted only of the most aerobically active components of the existing program. Differences favoring the intervention group were found for the spatial span and spatial working memory errors subscales of the Cambridge Neuropsychological Test Battery and for the accuracy subscale of the Attention Network Test. No differences between the control group and the intervention group were found on the Cognitive Assessment System (Fisher, et al., 2011).

Chaddock and colleagues (2010) investigated the association between aerobic fitness, hippocampal volume, and memory performance in children. Participants were divided into groups based on maximal oxygen consumption (VO_2 max) representing a lower-fit group and a higher-fit group. The results from the study indicate that higher-fit children performed significantly better on relational memory than the lower-fit children. Furthermore, higher-fit children showed larger bilateral hippocampal volume than the lower-fit children, which was additionally shown to be a mediating factor between fitness level and relational memory (Chaddock, et al., 2010). The findings suggest exercise may potentially benefit brain structure and function.

While little research exists to date exploring the impact of PA on implicit memory specifically, Pontifex and colleagues (2014) explored the effect of aerobic fitness on multiple memory systems. Participants were 88 undergraduate students with a mean age of 20.2 years (SD

= 2.2 years). Implicit memory was assessed via the SRTT and aerobic fitness was measured by $V0_2$ max. Results indicated individuals with poorer aerobic fitness demonstrated lower implicit memory acquisition (Pontifex, et al., 2014).

Overall, research indicates a direct relationship between both acute and chronic PA and cognition. Furthermore, emerging research suggests a relationship between aerobic fitness and memory, including implicit memory. No research has explored the relationship between PA and implicit memory, or the possible interaction between PA and concussion history with implicit memory. PA could potentially serve as a protective factor against concussions by way of cognitive reserve (Stern, 2002; Stern, 2003; Stern, 2009).

Cognitive reserve suggests similar brain injuries may have markedly different effects on individuals, showing clinical signs in one person and no visible signs in another (Stern, 2002; Stern, 2003; Stern, 2009). Cognitive reserve may take place actively or passively. The passive model of brain reserve (Katzman, 1993) or brain reserve capacity (Satz, 1993), suggests based on individual neuronal and synaptic differences, a person may have a higher or lower threshold for brain injury. The active model of cognitive reserve suggests the brain may be more efficient in some individuals, or simply better at compensating for injured areas of the brain (Stern, 2002; Stern, 2003; Stern, 2009). As PA has been demonstrated to increase cognitive abilities (Colcombe & Kramer, 2003; Sibley & Etnier, 2003; Smith et al., 2010; Fedewa & Ahn, 2011) it may be possible PA increases this brain reserve, potentially raising the threshold for injury or increasing the efficiency of the brain. The theory of cognitive reserve, therefore, suggests there may be an interaction between concussion history and PA on implicit memory.

2.12 Overview of Memory Systems

Memory is the learning and retention of new information (Bear, et al., 2007). Remembering something includes three distinct processes: acquiring the information, retaining the information, and retrieving the information (Bloom, Nelson, & Lazerson, 2005). The human memory system is broken down into two major systems: the declarative system and the non-declarative, or implicit, system. Figure 2 further illustrates the breakdown of human memory processes (Bear, et al., 2007).

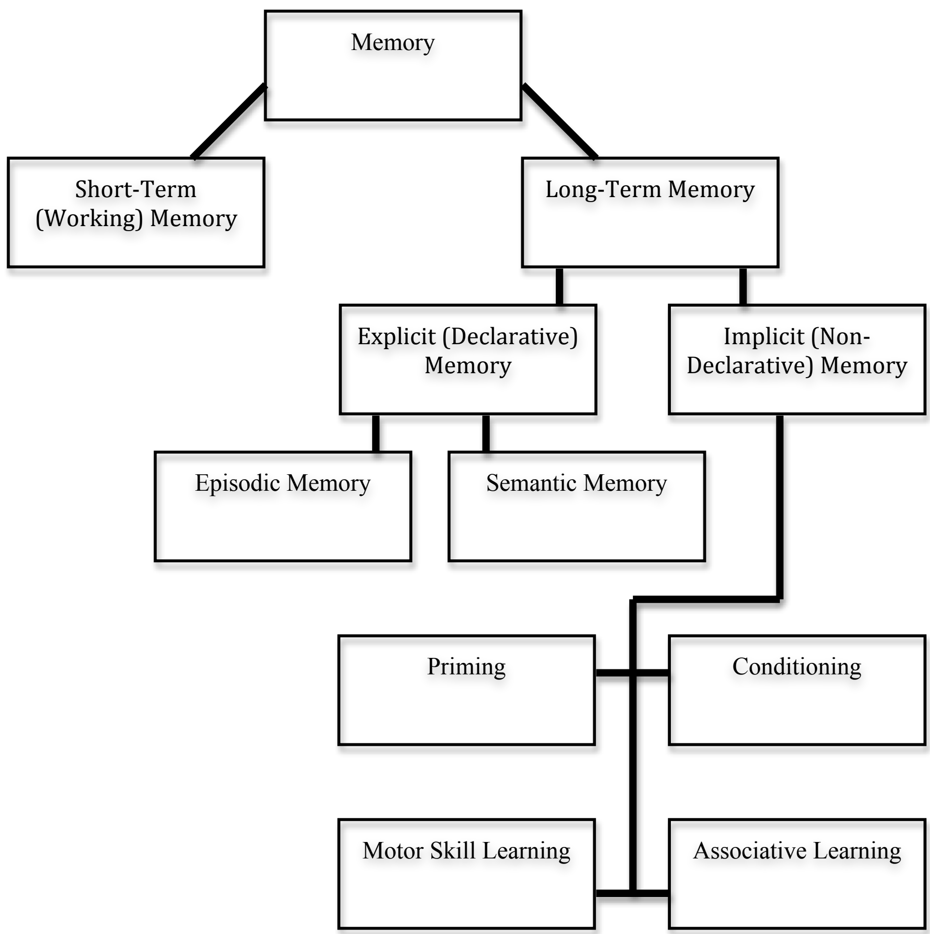

Figure 2. Illustration of the breakdown of human memory processes.

Working memory. Working memory is the ability to temporarily maintain and manipulate information. Working memory can be broken down in to 3 components: processing of phonologic information, processing of spatial information, and allocation of attention (Budson & Price, 2005; Budson, 2009). The area of the brain most involved in working memory is the prefrontal cortex (Budson & Price, 2005; Budson, 2009; Bear, et al., 2007); however, working memory relies heavily on both cortical and subcortical areas that are linked to the prefrontal cortex, forming a circuit (Budson & Price, 2005; Budson, 2009). While neurodegenerative diseases such as Alzheimer's and Parkinson's can interfere with working memory, so, too, can attentional disorders, such as attention deficit-hyperactivity disorder (Budson & Price, 2005; Budson, 2009).

Declarative system of memory. The declarative system of human memory is what enables someone to consciously recall information. Declarative memory is always explicit, that is the person is aware of learning new information and can consciously retrieve that information when called upon. This ability to retrieve information is usually the responsibility of the frontal lobes. The frontal lobes encode the information and retrieve the information stored, but do not directly play a role in the storage or retention of memories (Budson & Price, 2005; Budson, 2009). The information can be about events, referred to as episodic memory, or facts, called semantic memory.

Episodic memory is the ability for a person to recall specific events and place them in personal context (Budson, 2005). Dysfunction in episodic memory can be caused by lesions to the medial temporal lobes, the anterior thalamic nucleus, the mamillary body, the fornix, or the prefrontal cortex (Budson & Price, 2005; Budson, 2009). The frontal lobes are important in episodic memory, as they decide where focus should be geared, allowing an individual to omit unimportant information; any damage to the frontal lobes can cause distortions of memories (Budson & Price, 2005; Budson, 2009).

It is well known that the temporal lobe plays an important role in the formation of episodic declarative memories (Bear, et al., 2007; Budson & Price, 2005; Budson, 2009). In the famous case of the patient H. M., the medial portions of both temporal lobes, including the cortex, the amygdala, and the anterior portion of the hippocampus, were removed in an effort to control his temporal-lobe epilepsy (Bear, et al., 2007). As a result of this operation, H. M. could no longer form episodic memories. He could carry a conversation, but upon attempting to code these short-term memories into long-term memories, he would be unable to do so. After working with the same doctor for over 50 years, he still had to be introduced to her every time they met (Bear, et al., 2007). Interestingly, H. M. and other patients with similar brain injuries are still able to learn new skills, although they may be unaware of ever learning them. This separation points to the two distinct neural pathways of the two subsets of memory: declarative and non-declarative. Outside of the temporal lobes, the diencephalon, including the anterior and dorsomedial thalamus and the mamillary bodies, is implicated in declarative memory and amnesia, as well documented by the case of N. A. The patient N. A. had a lesion to his left dorsomedial thalamus and experienced severe anterograde and retrograde amnesia for a period of about 2 years prior to the accident. N. A.'s short-term memory remained intact and he was able to remember older memories; however, he could not form new memories, making meeting new people difficult. Watching TV was also troublesome, as during commercials he would forget most of what had happened previously (Bear, et al., 2007). Because of the similarities between N. A.'s and H. M.'s cases, it suggests the diencephalon and the temporal lobes are interconnected in declarative memory.

Episodic memory loss tends to follow a general pattern known as Ribot's law (Budson & Price, 2005; Budson, 2009). Ribot's law states that remote memories are robust and resistant to memory loss, whereas those memories more recently formed are vulnerable. Furthermore, the ability to form new memories is often disrupted as well (Budson & Price, 2005; Budson, 2009). This phenomenon is evident in the cases of both H. M. and N. A., where more remote memories remained intact for each patient, but more recent memories were distorted or unavailable.

Semantic memory is storage of general information and knowledge (Budson & Price, 2005; Budson, 2009). The region of the brain most responsible for semantic memory is the inferolateral temporal lobe (Budson & Price, 2005; Budson, 2009). Semantic memory may remain intact even with severe impairment on the episodic memory system, suggesting these are two separate systems. Alzheimer's disease most commonly disrupts semantic memory as the pathology interferes with the inferolateral temporal lobes (Budson & Price, 2005; Budson, 2009).

Disorders of declarative memory loss can be transient in nature, static, or progressive. Such events like a concussion, a seizure, or transient global amnesia are known to produce transient memory loss (Budson & Price, 2005; Budson, 2009). Memory loss can also be stable, as is the case with strokes, lesions, and encephalitis. Degenerative diseases, such as Alzheimer's disease, often produce progressive memory loss, where the memory loss gradually worsens over time (Budson & Price, 2005; Budson 2009). Furthermore, it is not uncommon for an individual to suffer declarative memory impairment with no impairment to the implicit system of memory.

Implicit system of memory. The non-declarative system, also referred to as the implicit system or procedural memory, is beyond what is consciously remembered. This system includes various types of remembering such as motor-skill learning (skills and habits), priming, and conditioning. It is suggested that implicit memory requires more effort to form, but it is less likely to be forgotten (Bear, et al., 2007). This is evident in the common phrase, when something is "like riding a bike," alluding to the difficult nature of forgetting a task once learned. With implicit memory, an individual will know how to complete a skill, but may be aware or unaware of this knowledge, and may have difficulty describing how the skill is performed. The acquisition of procedural memory can be explicit, such as the case when learning to ride a bike, or implicit, as is the circumstance when testing procedural memory via cognitive tests like the SRTT (Budson & Price, 2005).

The neural basis of implicit memory is difficult to fully ascertain, as different areas of the brain seem to control different types of implicit memory. In fact, research has demonstrated the cerebellum, the occipital cortex, the temporal cortex, and the striatum are all utilized in implicit memory (Nelson, 1995). As a new task is being learned, the basal ganglia, cerebellum, and supplementary motor area seem to become activated, according to research using functional imaging (Budson & Price, 2005; Budson, 2009).

It is clear, however, that the medial temporal lobe is not involved in implicit memory, as in the case of H.M. whose temporal lobes were removed and thereafter was able to learn new habits despite the inability to form new declarative memories. Furthermore, in early studies examining implicit learning in patients with Alzheimer's disease, those patients with Alzheimer's disease showed a decrease in RT similar to control participants on the SRTT, thus the authors contend the medial temporal lobes are not necessary for procedural learning (Knopman & Nissen, 1987). While it remains difficult to pinpoint the region or regions necessary for implicit learning, as Alzheimer's patients typically have a normally functioning striatum, it may be hypothesized that the striatum is implicated in implicit memory (Knopman & Nissen, 1987; Nelson, 1995).

Some degenerative diseases have been known to impact implicit memory, such as Parkinson's disease, Huntington's disease, and olivopontocerebellar degeneration (Budson & Price, 2005; Budson, 2009), as these disease effect the basal ganglia and the cerebellum. Additionally, people suffering from depression have demonstrated deficiencies in implicit memory as well, perhaps because functioning of the basal ganglia seems to be disrupted during depression (Budson & Price, 2005; Budson, 2009). Given the diffuse nature of traumatic brain injury, it is possible that the basal ganglia may suffer insult at a cellular level and therefore impairment of implicit memory may present. Furthermore, given the location of the basal ganglia in regions next to major cerebral arteries, the basal ganglia may be more vulnerable to concussive effects from the neurometabolic cascade noted in the acute phase of injury.

2.13 Implicit Memory in Normal Development

Evidence of implicit learning can be seen as early as 3 months old. Rovee-Collier and Sullivan (1980) demonstrated implicit memory in 3 month-old infants, who were able to learn how to move a crib mobile by kicking their feet. Similarly, Haith and colleagues (1988) explored expectation and anticipation in 12 3.5 month-old babies. The infants were shown images of projected slides that appeared to the left or right of the visual center, and moved up and down. In the alternating series, the slides would appear on the left, followed by the right, with an interval in between of 1,100 ms. A separate, random series was projected, where the slides were arranged randomly with differing between-slide intervals. The infants' right eyes were videotaped during the presentation of the slides to determine if any anticipatory eye movements occurred, and if RTs decreased across trials of a repeating pattern. Results indicated there was a higher likelihood for anticipatory eye shift in the alternating (i.e., predictable) series than for the irregular series (Haith, et al., 1988). Furthermore, the RT for these eye shifts decreased considerably from baseline in the alternating series, while the irregular series showed no difference from baseline (Haith, et al., 1988). These findings indicate there is some form of implicit learning occurring, in that infants can develop expectations for events and carry out anticipatory actions.

While the studies done by Rovee-Collier and Sullivan (1980) and Haith et al. (1988) demonstrate implicit learning can occur from a young age, other studies demonstrate the age-related differences in implicit learning across the lifespan (Hodel, Markant, Van Den Heuvel, Cirilli-Raether, & Thomas, 2014; Janacsek, Fiser, & Nemeth, 2012; Thomas, et al., 2004). Hodel and colleagues and Janacsek and colleagues explored developmental differences in implicit sequence learning on the SRTT. Janacsek et al. found both preschoolers and adults were able to demonstrate implicit learning, however, adults were found to have higher levels of sequence specific learning on the SRTT than the preschoolers (Hodel et al., 2014). Further investigating these developmental differences, Janacsek and colleagues (2012) tested implicit sequence learning across the lifespan in participants ages 4 to 85 years old, clustered into 9 different age groups (i.e. 4-6, 7-8, 9-10, 11-12, 14-17, 18-29, 30-44, 45-59, and 60-85 years old). The RTs were significantly different across the age groups. RTs decreased significantly between each group from 4 to 29 years of age and then significantly increased after 44 years of age (Janacsek et al., 2012). Contrary to Hodel et al., the authors conclude there is a gradual decline in implicit learning across the lifespan (Janacsek, et al., 2012).

Thomas et al. (2004) also researched developmental differences on implicit learning, but further explored these differences by employing neuroimaging. Thomas and colleagues utilized fMRI to decipher which brain regions were called upon during the SRT task in children versus adults. The results of their study indicate that adults recruited cortical regions, including the premotor cortex, to complete the task, whereas children used predominantly subcortical regions of the brain, specifically the putamen (Thomas, et al., 2004). Given these findings, there is support for developmental differences in which regions of the brain are recruited during the implicit sequence learning task, and there tends to be a shift from subcortical to cortical from childhood to adulthood (Thomas, et al., 2004).

Previous research has suggested the regions of the brain most called upon during implicit learning are those more sub-cortical brain regions, such as the basal ganglia (Rauch, et al., 1997; Bischoff-Grethe, Goedert, Willingham, & Grafton, 2004). These regions mature early in development and are believed to be mature by middle childhood, further supporting the abilities for infants to demonstrate implicit learning (Haith, et al., 1988). Research has demonstrated some developmental differences in implicit learning (Hodel, et al., 2014; Janacsek, et al., 2012; & Thomas, et al., 2004); moreover, developmental differences can be noted not just behaviorally, but through neuroimaging as well, as a shift in the recruited region of the brain (Thomas, et al., 2004).

2.14 Sport-Related Concussion and Implicit Memory

Recent research is attempting to explore the effect, if any, SRC have on implicit memory. Studies suggest athletes with a history of concussions have significantly reduced implicit motor learning compared to control athletes (De Beaumont, et al., 2012; De Beaumont, et al., 2013). De Beaumont and colleagues tested university athletes between the ages of 19-27 years old (mean age = 23.4 years) who had a history of at least 2 concussions (average = 2.87 concussions). These athletes had sustained the last concussion at least 9 months prior to testing (average time since last concussion = 13.74 months). Those athletes with a history of concussion exhibited markedly reduced implicit motor learning than their counterparts with no history of concussion, as demonstrated on the SRTT (De Beaumont, et al., 2012). This research reveals implicit memory may in fact be inhibited following a concussion, and these deficits may continue to present many months after the resolution of other symptoms.

Furthermore, similar effects are seen later in life with retired university athletes, ages 51-75 years old (mean age = 60.87 years). De Beaumont et al., (2013) studied retired athletes with a history of one or more concussions, who experienced the most recent concussion on average 37 years prior to testing. Those athletes with a history of concussion showed significantly less improvement on the SRTT than the control athletes who had no prior history of concussion (De Beaumont, et al., 2013), again demonstrating the lingering effects concussions may have on implicit memory in an adult population.

At this time, research has yet to explore the effects SRC may have on implicit memory in youth and adolescents. Some researchers, however, have examined implicit memory following moderate to severe traumatic brain injury in children (Lah, Epps, Levick, & Parry, 2011; Shum, Jamieson, Bahr, & Wallace, 1999; Ward, Shum, Dick, McKinlay, & Baker-Tweney, 2004; Ward, Shum, Wallace, & Boon, 2002). The majority of these studies suggest implicit memory remained intact for those children who sustained a moderate to severe traumatic brain injury (TBI; Shum, et al., 1999; Ward et al., 2004; Ward et al., 2002).

One of the few studies to demonstrate impairments in implicit memory following severe TBI was conducted by Lah and colleagues (2011), with children ages 8 months to 13 years and 7 months (average age = 12.1 years) who had sustained the injury at least 12 months prior (average time = 6.5 years). Lah et al., found impairments in implicit memory as demonstrated by performance on the fragmented pictures, or picture-completion, task. Furthermore, when exploring the effect of age on implicit memory, those children who experienced the injury during late childhood (age at injury ≥ 6 years) did not exhibit differences from non-injured children in implicit memory performance, while those who experienced the injury during early childhood (age at injury < 6 years) demonstrated deficits in implicit memory (Lah, et al., 2011). Previous research on moderate to severe TBI in children had not demonstrated these effects on implicit memory.

Previous research has demonstrated implicit memory acquisition following brain injury may remain intact for children and adolescents (Shum et al., 1999; Ward, et al., 2002; Ward, et al., 2004). Shum et al., (1999) tested implicit memory on children ages 4-14 years old (mean = 8.4 years) who had sustained a severe TBI at least one year prior to the study (average time = 29 months). The experimental group of participants with a history of TBI was compared to a control group with no history of TBI. Results indicated when compared to a control group of non-injured participants, the extent to which priming took place was not significantly different between the two groups, demonstrating no difference in implicit memory after severe TBI (Shum et al., 1999). Research by Ward and colleagues (2002) explored implicit memory in children ages 8-15 years old (mean = 9.5 years) who had sustained a moderate to severe TBI, and were at least 9 months out from injury (average time = 30.7 months). Implicit memory, both motor perceptual and cognitive, was preserved in children with moderate to severe TBI (Ward, et al., 2002). Ward and colleagues (2004) interviewed parents of children who had sustained a TBI, ranging from mild to severe. The results indicated few of the children had any impairments of implicit memory. Two parents, however, did express their children had trouble associating negative consequences to actions, allowing these children to take unnecessary risks. This failure to learn from negative consequences may be due to poor associative learning, or implicit memory, but may also be due to impulsiveness rather than a lack of associative learning, or implicit memory

(Ward, et al., 2004). The findings from previous research suggest implicit memory may not be impacted by moderate to severe brain injury in children and adolescents.

These findings of preserved implicit memory are consistent with findings in an adult population with moderate to severe TBI (Ewert, Levin, Watson & Kalisky, 1989; Shum, Sweeper, & Murray, 1996), which is markedly different from the findings in adults with concussions (De Beaumont, et al., 2012; De Beaumont, et al., 2013). The differences in findings between concussions and moderate to severe TBI demonstrates there may be something in the nature of a mild brain injury that has the ability to impair implicit memory. Some research suggests that because the anterior region of the brain is the area most affected by moderate to severe TBI, rather than the posterior region where implicit memory is believed to be controlled, implicit memory should remain largely intact following a moderate to severe TBI (Shum, et al., 1999). Because concussions are a diffuse injury, affecting the entire brain, it is more probable that implicit memory would be affected.

2.15 Summary and Conclusions

Given concussion diagnosis in high school athletes has increased from a rate of 0.23 in 2006 to a rate of 0.51 in 2012 (Rosenthal, et al., 2014), it is necessary to continue to research the effects of concussions. Previous research has suggested a history of concussion increases the risk for subsequent concussions (Gerberich, et al., 1983; Guskiewicz, et al., 2000; Guskiewicz, et al., 2003; Zemper, 2003), although the direct mechanism is not understood. Potentially, an athlete’s style of play may put an athlete at greater risk for subsequent concussions (McCrory, et al., 2001). With regards to the current study, an athlete who has experienced a concussion resulting in decrements in implicit memory may engage in more risk-taking behaviors in sport, increasing the risk for subsequent injury. The effect of concussions on implicit memory has not yet been explored in an adolescent population. The little research that has been conducted on concussions and implicit memory was in an adult population, and demonstrated significant deficiencies in implicit memory in athletes with a history of concussion compared to athletes with no history of concussion (De Beaumont, et al., 2012; De Beaumont, et al., 2013). Furthermore, the role of PA and implicit memory has not yet been explored, however, aerobic fitness has been demonstrated to have a positive relationship with implicit memory in healthy, college students (Pontifex, et al., 2014), suggesting a similar effect may be noted in the relationship between PA and implicit memory. Furthermore, by way of cognitive reserve, PA and concussion history may have an interactive effect on implicit memory. Specifically, if concussions result in impaired implicit memory in adolescents, these impairments may not be noted in higher active individuals. Because PA is related to better cognitive functioning, including memory, PA level may protect against some of the effects of concussion. Given the current findings in the literature to date, the current study addresses necessary gaps regarding the effects of concussions on adolescents, the role PA level plays in implicit memory acquisition in adolescents, and the potential interaction between concussion history and PA on implicit memory in adolescents.

CHAPTER 3

METHODOLOGY

3.1 Research Design and Participants

The study design was cross-sectional. The independent variables were concussion history and PA. The dependent variable was implicit memory acquisition. Covariates were sex, socioeconomic status (SES), race, and age. SES was measured by participants indicating whether or not they had been recipients of the free or reduced lunch program in the past. Participants came from a convenience sample of local, Lansing-area high schools. Researchers recruited participants through coaches, athletic trainers, and athletic directors at the local high schools. Eight schools were approached and five agreed to participate. All participants were high school athletes, both male and female, between the ages of 13 and 19 years. All participants competed in at least one sport, either with a club or the school, within the last year. Participants were separated into the following groups based on concussion history: no previous concussion, one or more previous concussion(s). PA was measured as a continuous variable based on scores from the PAQ-A.

An *a priori* power analysis was conducted to determine sample size. Approximately 77 participants were necessary for 80 percent power for detecting an effect size of .15, when utilizing a level of significance of $\alpha = 0.05$ across three predictors of concussion history, PA, and an interaction term between concussion history and PA. The current study yielded a sample size of 55 participants, after those athletes whose data was insufficient were removed. Those athletes who failed to meet the 90 percent response accuracy criterion were removed, as were those athletes whose PAQ-A data was incomplete. With a sample size of 55, three predictor variables, a level of significance of $\alpha = 0.05$, and a power of 80 percent, a sensitivity analysis determined the sample would be capable of recognizing an effect size of .21 or larger. After further exploration of the data, individuals with a positive implicit memory ratio were removed, as a positive score would indicate no implicit learning had occurred. Therefore, a final sample size of 51 resulted. A sensitivity analysis revealed with three predictor variables, a level of significance of $\alpha = 0.05$, and a power of 80 percent, the sample would recognize an effect size of .23 or larger.

3.2 Inclusionary Criteria for Athletes with and without a History of Concussion

Athletes were grouped together based on their concussion histories (i.e., no previous concussion, one or more previous concussion(s)). Concussion history was gathered through the demographic form, which was completed by the athlete. The athletes answered a question regarding the number of previous concussions that were diagnosed by an athletic trainer or doctor, and gave approximate dates for any previous concussions. Further information was gathered regarding time spent sidelined from activity and any amnesia the athlete may have incurred as a result of the concussion(s), as well as whether or not the concussion resulted in a LOC. Athletes were included in the no previous concussion group if they reported having no history of concussions. Those athletes who reported having sustained at least one prior concussion were included in the concussion history group. Utilizing self-report measures for concussion history, while perhaps less stringent than accessing medical records, was more appropriate for the current study, and has repeatedly been used in similar studies.

3.3 Exclusionary Criteria for Athletes with and without a History of Concussion

Athletes were excluded from participation if they had not been medically cleared to play after sustaining a concussion in the last three months. Therefore any athlete currently suffering from a suspected or confirmed concussion was excluded from the study. Those athletes who had undergone brain surgery or had a severe history of intracranial pathology (e.g., subdural hematoma) as determined by a positive CT scan or MRI were excluded from the current study. In addition, participants were required to meet a 90 percent response accuracy criterion on the SRTT to be included in any analyses.

3.4 Instrumentation

Demographics and concussion history. Demographic variables including age, height, weight, sex, race/ethnicity, and approximate grade point average were obtained via a demographic form (see Appendix A) completed by the participant. Information regarding the most recent sport in which the athlete participated was also gathered. Furthermore, athletes answered questions regarding possible learning disabilities, history of headaches, seizures, meningitis, substance abuse, and psychiatric conditions, as well as concussion history.

Implicit memory. Implicit memory was assessed using the SRTT. The SRTT is a four-choice RT task. Participants were presented with a visual stimulus (i.e., a red dot) and were directed to respond as quickly and as accurately as possible by striking a button on a keypad. The stimulus was a small, red dot (0.4° radius) that presented in one of four boxes horizontally organized on the screen, each with 2° horizontal and vertical visual angles (see Figure 3). Each box on the screen corresponded to a button on a keypad to be pressed by the middle or index finger of the right or left hand, depending on the position of the stimulus. The left middle and index fingers were positioned over "D" and "F," respectively, and corresponded to boxes 1 and 2. The right index and middle fingers were on "J" and "K" and corresponded to boxes 3 and 4 on the screen. When the stimulus was presented in one of the boxes, the participant was to choose the appropriate key that corresponded to that box. A trial occurred each time the stimulus was presented and the participant responded. The duration of each trial was dependent upon the participant's response time.

A sequence consisted of 12 trials or stimulus presentations. A block consisted of 13 sequences, resulting in 156 total stimulus presentations in each block. Within each block there were both patterned sequences and random sequences. In a patterned sequence, the stimulus presented 12 times in a repeating pattern. In the random sequence, the stimulus presented 12 times in no particular order. RT was measured for both sequential and random trials. Previous literature indicates setting a response accuracy criterion is appropriate; therefore the current study used a 90 percent response accuracy criterion as used in previous research (Pontifex, et al., 2014). Any block in which an athlete failed to respond accurately at least 90 percent of the time was omitted from analysis. The response accuracy criterion is set in order to ensure the task is measuring implicit memory. The SRTT is a simple four-choice task, therefore it is assumed any participant not reaching the 90 percent response accuracy criterion is not actively participating in the task and thus the task will not measure implicit memory.

The participants first completed 40 practice trials, in which no repeating sequence was present. Following the practice trial, the participants completed five blocks of FOC. FOC (i.e., patterned) sequence learning focuses on the knowledge of the immediate preceding position to predict an upcoming position. The FOC sequence consists of 12 trials where each trial provides probabilistically predictive information 67% of the time.

The SRTT has been a demonstrated measure of implicit memory. Willingham, Nissen, and Bullemer (1989) explored subjects' implicit memory and declarative memory acquisition using the SRTT. Specifically, participants who had no explicit knowledge of the repeating sequence still showed performance improvements by a decrease in RT by nearly 100 milliseconds. These results confirm the ability of the SRTT to measure implicit memory.

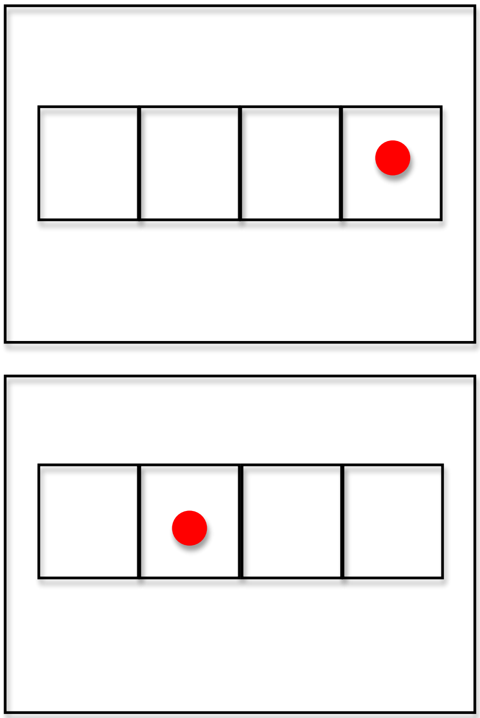

Figure 3. Illustration of two trials on the SRTT. In the first trial the stimulus is presented in box 4, requiring the participant to strike the key that corresponds with box 4 (k). In the second trial the stimulus is presented in box 2, requiring the participant to strike the key that corresponds with box 2 (f).

Physical activity. Participants' PA was measured using the PAQ-A (see Appendix B). The PAQ-A is a self-report survey where participants recall PA over the past 7 days. A PA score was then obtained from the 8 items on the survey, each scored on a 5-point scale. The final score was the average of the 8 items, resulting in a score between 1 and 5.

The adolescent version of the PAQ was developed for use in a high school population; therefore it is appropriate for use in the current study. Furthermore, previous research exploring the convergent validity of the PAQ-A demonstrated it to be significantly correlated with other self-report measures of PA, including the Leisure Time Exercise Questionnaire (r = 0.57), an activity rating ($r = 0.73$), and the 7-day Physical Activity Recall Interview ($r = 0.59$) (Kowalski, Crocker, & Kowalski, 1997). Additionally, the PAQ-A was also demonstrated to be related to the Caltrac motion sensor ($r = 0.33$) (Kowalski, et al., 1997). In previous research, the PAQ-A has been used to classify adolescents into different activity levels (Kowalski, et al., 1997), thus it was appropriate to use the PAQ-A in the current study to assess participants' level of PA.

3.5 Procedures

Before data collection began, approval from the Michigan State University Institutional Review Board was obtained. Parental written informed consent and child assent were obtained from parents of the participants and the participants themselves, respectively. Likewise, for those participants who were at least 18 years old, written informed consent was obtained before data collection. Data were collected at the various high schools in small groups of individual athletes or teams. The high schools had ample space for conducting the necessary testing and data collection. Five laptop computers, outfitted with the SRTT, were brought to the high schools for testing.

Members of the research team reported to the local high schools on specified dates to collect data. All researchers underwent training for human subjects through the Michigan State University Institutional Review Board website.

Participants were instructed to complete the demographic questionnaire and the PAQ-A in groups of one to five athletes. Completion of the demographic questionnaire and the PAQ-A took approximately 15 minutes. Athletes completed the SRTT individually on the laptops in small groups of no more than 5 athletes, which took approximately 20 minutes. As only five laptops were available for testing, the first five athletes were assigned to take the SRTT. Those athletes who were not taking the SRTT completed the demographic form and PAQ-A. Upon completion of one task, the athlete moved to the next task to complete.

When taking the SRTT, athletes were instructed to complete a simple RT task in which they were to correctly identify the block where the stimulus, a small red dot, would appear. The location of the stimulus varied among the four possible locations across trials. Researchers explained to the athletes the placement of the fingers on the keypad and how each key corresponded to a box on the screen (e.g., left middle finger on "D" corresponded with box 1). A key press was required for the next trial to begin. After the practice session and after each block, the athlete was prompted with directions on the screen to press "enter" when they were ready to continue, allowing the athletes to take a short break if necessary. At the completion of the test, the program ended automatically.

The total time to complete the testing was approximately 35 to 45 minutes. Each participant was given a unique ID number, and no other identifying information appeared on any data document. Athletes were instructed to insert this ID number when beginning the SRTT by a prompt on the screen. Likewise, athletes wrote their unique ID numbers on the top of the demographic forms and PAQ-A. The results from the SRTT were then matched to the paper-and-pencil demographic form and PAQ-A through the use of the ID number.

3.6 Data Analysis

The statistical analysis plan involved performing descriptive statistics and multiple regression analyses to examine implicit memory related to concussion history and PA. Implicit memory acquisition was a measurement of RT on the SRTT, specifically the difference in RT between sequence and random trials. Faster RT on sequence trials versus random trials indicated implicit memory had occurred. Prior to analysis, all variables were screened for normality.

SRTT data pre-processing and analysis. The SRTT yielded measurements for RT on both the sequence trials and the random trials. To obtain a measure of implicit memory, the average RT on the random trials were subtracted from the average RT on the sequence trials, relative to the RT on the random trials. Lower negative values indicated greater implicit memory acquisition ([(sequence trials – random trials)/random trials] x 100). Positive values indicated the average RT for sequence trials was longer than the average RT for random trials, which would indicate a lack of implicit learning. These scores of implicit memory acquisition were compared across concussion history groups (i.e., no concussion, one or more previous concussion(s)) and across PA, as well as any possible interaction, utilizing multiple regression analyses.

Evaluation of hypotheses and specific aims. In order to evaluate how concussion history (i.e., no previous concussion, one or more previous concussion(s)) (specific aim 1) and PA affect implicit memory acquisition in adolescents (specific aim 2), multiple regression analyses were used. A subsequent model explored any potential interaction (specific aim 3). The independent variables were concussion history, divided into the following groups: no previous concussion, one or more previous concussion(s) and PA, scored as a continuous variable. Sex, SES, race, and age were entered into the model first. The dependent variable was implicit memory, measured as the difference between the average RT on sequence trials and the average RT on random trials, relative to the RT on random trials. It was hypothesized that concussion history would be inversely related to implicit memory acquisition and PA would be positively related to implicit memory. All analyses were run on SPSS version 21.0. Significance was set at $p < .05$.

CHAPTER 4

RESULTS

4.1 Demographics

A total of 64 high school athletes (29 female, 35 male) participated in the current study, 46 (25 female, 21 male) had no history of concussion, compared to 18 athletes (4 female, 14 male) with a history of at least one previous concussion. All athletes completing the study were asymptomatic at the time of the study. The sports of track, cheerleading, football, lacrosse, boys' and girls' basketball, girls' volleyball, baseball, wrestling, softball, and girls' soccer were represented in the sample. The number of participants who competed in each sport can be found in Table 2. On average, athletes had 2.42 years of experience (SD = 1.20) in sport at the high school level. Independent t-tests revealed no significant difference in average years of experience between the concussion history groups ($t = .655$, $p = .515$). Table 2 shows specific information about the participants regarding their self-report grade point averages. An independent t-test revealed no differences between concussion history groups on GPA ($t = 1.504$, $p = .138$). Participants also reported their race and ethnicity; specific frequencies can be found in Table 2. Additionally, 23 athletes (35.9%) reported receiving free or reduced lunch. Of the 46 athletes with no previous concussion, 17 (37.0%) reported receiving free or reduced lunch and 29 (63.0%) reported never having received free or reduced lunch. Six of the 18 athletes with a history of concussion (33.3%) reported having received free or reduced lunch.

Independent t-tests were conducted to evaluate any potential differences between the groups. There were no significant differences between the history of concussion group and the no history of concussion group regarding age ($t = -1.252$, $p = .215$), height ($t = -1.054$, $p = .296$), or weight (t = -1.126, p = 0.265). A summary of the demographic data for age, height, and weight can be found in Table 2.

Table 2.

Demographic Information for Asymptomatic Athletes with a History of Concussion (n = 18) and Athletes with no History of Concussion (n=46)

	History of Concussion	No History of Concussion	Total
Sport[a]			
Girls' Volleyball	2 (11.1)	13 (28.3)	15 (23.4)
Track	5 (27.8)	8 (17.4)	13 (20.3)
Baseball	6 (33.3)	4 (8.7)	10 (15.6)
Football	3 (16.7)	5 (10.9)	8 (12.5)
Girls' Basketball	1 (5.6)	3 (6.5)	4 (6.3)
Girls' Soccer	0 (0.0)	4 (8.7)	4 (6.3)
Wrestling	0 (0.0)	3 (6.5)	3 (4.7)
Boys' Basketball	0 (0.0)	3 (6.5)	3 (4.7)
Lacrosse	0 (0.0)	2 (4.3)	2 (3.1)
Cheerleading	0 (0.0)	1 (2.2)	1 (1.6)
Softball	1 (5.6)	0 (0.0)	1 (1.6)
GPA[a]			
3.5 – 4.4	7 (38.9)	28 (60.9)	35 (54.7)
2.5 – 3.4	9 (50.0)	15 (32.6)	24 (37.5)
2.5 or below	2 (11.1)	3 (6.5)	5 (7.8)

Table 2 (cont'd)

	History of Concussion	No History of Concussion	Total
Race or Ethnicity[a]			
White	12 (66.7)	30 (65.2)	42 (65.6)
Identifies with Multiple Races or Ethnicities	4 (22.2)	8 (17.4)	12 (18.8)
Black or African American	1 (5.6)	4 (8.7)	5 (7.8)
Hispanic or Latino	1 (5.6)	2 (4.3)	3 (4.7)
Other	0 (0.0)	2 (4.3)	2 (3.1)
Height[b]			
Males	70.07 (4.80)	71.30 (2.72)	70.79 (3.70)
Females	66.63 (2.93)	65.36 (3.60)	65.53 (3.49)
Weight[b]			
Males	189.46 (42.98)	195.47 (47.96)	193.03 (45.38)
Females	136.75 (8.50)	137.42 (22.76)	137.33 (21.26)
Age[b]			
Males	16.86 (1.34)	16.57 (1.17)	16.69 (1.23)
Females	16.25 (.50)	16.08 (1.19)	16.10 (1.11)

Notes:
[a]values are written as *n* (%)
[b]values are written as mean (SD)

The history of concussion group had a reported average of 1.5 (SD = .86) previous concussions, ranging from 1 to 4 previous injuries. All athletes in the concussion history group were at least 5-months post-injury. The average time since the last concussion was approximately 26 months (SD = 23.48 months), with all athletes between 5 and 72 months. Eighteen athletes reported a total of 27 concussions; 12 athletes reported one previous concussion, four athletes reported two previous concussions, one athlete reported three previous concussions, and one athlete reported four previous concussions. Of the 27 total concussions previously incurred, five of these concussions resulted in LOC, nine resulted in some anterograde amnesia, and six resulted in some retrograde amnesia, as reported by the athletes.

Scores from the SRTT are listed by group in Table 3. Overall, participants recorded an average RT ratio of -4.19 (SD = 4.91) on the first block of the SRTT. Asymptomatic athletes with a history of concussion had an average RT of -3.11 (SD = 5.34), while those athletes with no history of concussion had an average RT of -4.61 (SD = 4.73). An independent samples t-test revealed no significant difference between concussion history groups on RT on the SRTT (t = -1.103, p = .274). Positive values indicate a slower RT on sequence trials compared to random trials, suggesting no implicit learning as occurred. Information on RT by concussion history groups can be found in Table 3.

Table 3.

Implicit Memory Scores for Asymptomatic Athletes with a History of Concussion (n = 18) and Athletes with no History of Concussion (n=46)

	History of Concussion	No History of Concussion	Total
Implicit Memory Ratio			
Mean (SD)	-3.11 (5.34)	-4.61 (4.73)	-4.19 (4.91)
Minimum	-10.50	-16.00	-16.00
Maximum	12.29	10.69	12.29

With regard to level of PA, athletes recorded an average of 2.87 (SD = 0.61) on the PAQ-A. Eight of the reporting participants' PAQ-A data were insufficient, and therefore were not included in this analysis. The history of concussion group had an average score of 3.11 (SD =

.63) on the PAQ-A, while the no history of concussion group had an average score of 2.78 (SD = .59). An independent samples t-test revealed no significant difference between concussion history groups on level of PA (t = -1.945, p = .057), although there was a trend for the concussion history group to have a higher PA level. Specific information regarding the PAQ-A scores by group can be found in Table 4.

Table 4.

Physical Activity Scores for Asymptomatic Athletes with a History of Concussion (n = 17) and Athletes with no History of Concussion (n = 39)

	History of Concussion	No History of Concussion	Total
PAQ-A[c]			
Mean (SD)	3.11 (.63)	2.78 (.59)	2.87 (.61)
Minimum	2.23	1.03	1.03
Maximum	4.30	4.24	4.30

Upon exploring the data, in the first block of the SRTT, six of the 64 participants failed to meet the 90 percent response accuracy criterion and were therefore removed. Specific demographic information regarding the remaining 58 participants can be found in Table 5. One of the six athletes removed had previously sustained a concussion. The six athletes removed from analysis participated in multiple sports: one from football, two from girls' volleyball, one from wrestling, and two from track. Three of the athletes removed from analysis were female. The participants who were removed from analysis favored heavily on the nonwhite population (4 of the original 22, 18.18%) and on those who previously received free or reduced lunch (5 of the original 23, 21.74%). In the second block, nine of the 64 participants did not reach the 90 percent response accuracy threshold. In the third, fourth, and fifth blocks, 17, 16, and 18, did not meet the necessary response accuracy, respectively. When assessing across all five blocks, 30 of the 64 participants did not reach the 90 percent response accuracy criterion for all five blocks.

Table 5.

Demographic Information for Asymptomatic Athletes with a History of Concussion (n = 17) and Athletes with no History of Concussion (n=41)

	History of Concussion	No History of Concussion	Total
Sport[a]			
Girls' Volleyball	1 (5.9)	12(29.3)	13 (22.4)
Track	5 (29.4)	6 (14.6)	11 (19.0)
Baseball	6 (35.3)	4 (9.8)	10 (17.2)
Football	3 (17.6)	4 (9.8)	7 (12.1)
Girls' Basketball	1 (5.9)	3 (7.3)	4 (6.9)
Girls' Soccer	0 (0.0)	4 (9.8)	4 (6.9)
Wrestling	0 (0.0)	2 (4.9)	2 (3.4)
Boys' Basketball	0 (0.0)	3 (7.3)	3 (5.2)
Lacrosse	0 (0.0)	2 (4.9)	2 (3.4)
Cheerleading	0 (0.0)	1 (2.4)	1 (1.7)
Softball	1 (5.9)	0 (0.0)	1 (1.7)
GPA[a]			
3.5 – 4.4	6 (35.3)	26 (63.4)	32 (55.2)
2.5 – 3.4	9 (52.9)	12 (29.3)	21 (36.2)
2.5 or below	2 (11.8)	3 (7.3)	5 (8.6)

Table 5 (cont'd)

	History of Concussion	No History of Concussion	Total
Race or Ethnicity[a]			
White	11 (64.7)	29 (70.7)	40 (69.0)
Identifies with Multiple Races or Ethnicities	4 (23.5)	8 (19.5)	12 (20.7)
Black or African American	1 (5.9)	1 (2.4)	2 (3.4)
Hispanic or Latino	1 (5.9)	2 (4.9)	3 (5.2)
Other	0 (0.0)	1 (2.4)	1 (1.7)
Height[b]			
Males	70.07 (4.80)	71.39 (2.81)	70.81 (3.80)
Females	66.17 (3.40)	65.39 (3.71)	65.48 (3.62)
Weight[b]			
Males	189.46 (42.98)	197.00 (49.72)	193.62 (46.16)
Females	134.00 (7.94)	136.41 (22.15)	136.13 (20.91)
Age[b]			
Males	16.86 (1.35)	16.44 (1.20)	16.63 (1.26)
Females	16.00 (.00)	16.13 (1.14)	16.12 (1.07)

Notes:
[a]values are written as *n* (%)
[b]values are written as mean (SD)

The remaining 58 participants had an average RT of -4.69 (SD = 4.04) and an average PAQ-A score of 2.88 (SD = .61). Specific information on RT from the SRTT and scores from the PAQ-A by concussion history group can be found in Tables 6 and 7.

Table 6.

Implicit Memory Scores for Asymptomatic Athletes with a History of Concussion (n = 17) and Athletes with no History of Concussion (n=41)

	History of Concussion	No History of Concussion	Total
Implicit Memory Ratio			
Mean (SD)	-4.01 (3.82)	-4.98 (4.14)	-4.69 (4.04)
Minimum	-10.50	-16.00	-16.00
Maximum	3.76	3.71	3.76

Table 7.

Physical Activity Scores for Asymptomatic Athletes with a History of Concussion (n = 17) and Athletes with no History of Concussion (n=41)

	History of Concussion	No History of Concussion	Total
PAQ-A[c]			
Mean (SD)	3.13 (.64)	2.78 (.57)	2.88 (.61)
Minimum	2.23	1.03	1.03
Maximum	4.30	4.24	4.30

The original sample of 64 participants was compared to the resulting samples of 58 and 34 participants, only including those who reached the 90 percent response accuracy threshold across one and across all five blocks of the SRTT, respectively. Specific information regarding these samples can be found in Figure 4. Overall, the resulting sample of 34 was not considerably different from the original sample of 64 participants. However, the resulting sample included a smaller percentage of males, suggesting that a larger proportion of males failed to reach the 90 percent response accuracy criterion across all five blocks of the SRTT.

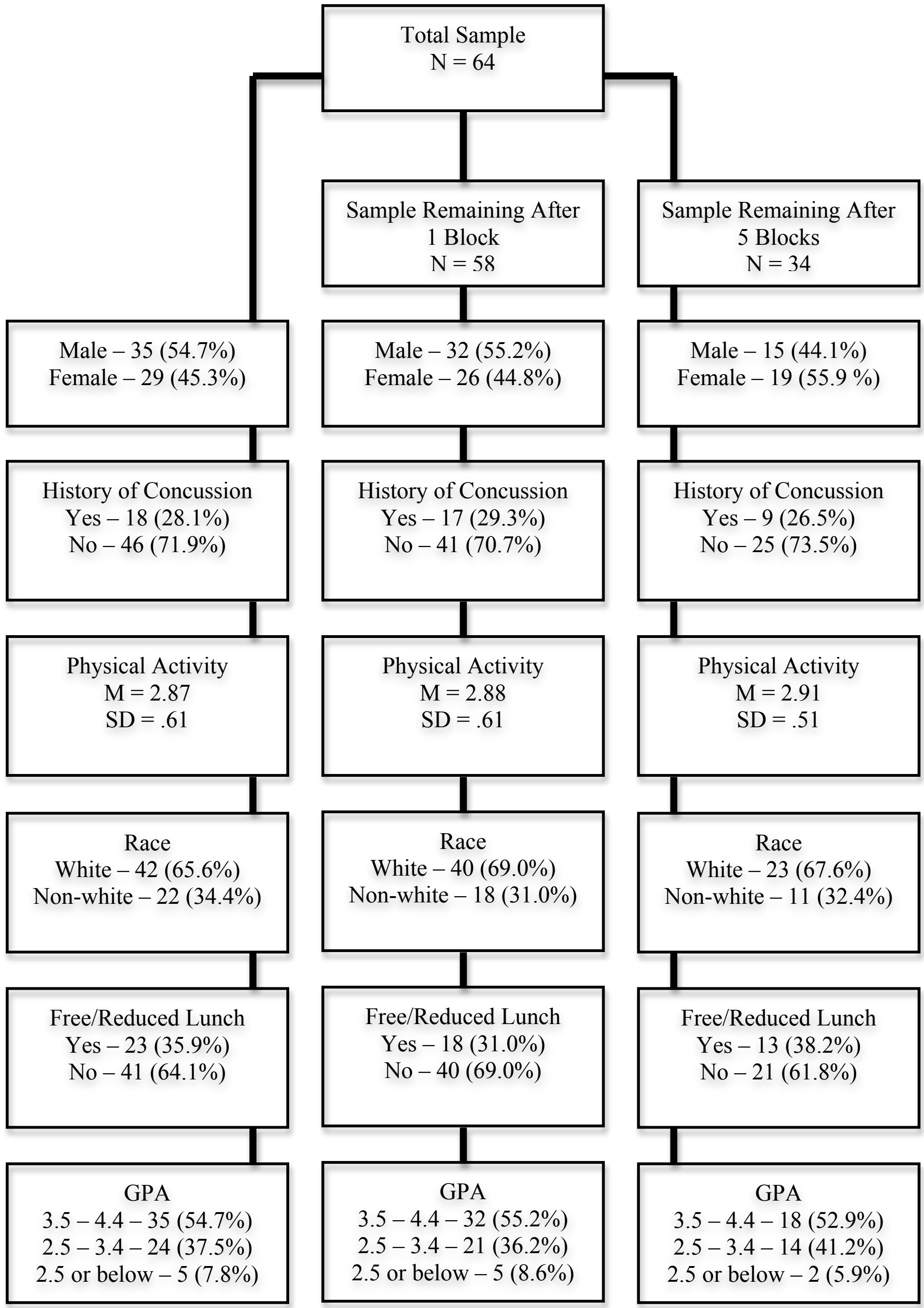

Figure 4. Sample characteristics for the original sample and the reduced sample of participants achieving 90% response accuracy across one and five blocks of the SRTT.

Those athletes with a positive implicit memory ratio were compared to those athletes with a negative implicit memory ratio on the first block of the SRTT, after removing individuals who failed to meet the 90 percent response accuracy criterion. Independent groups t-tests revealed no significant differences between groups on age, height, weight, or GPA at a significance level of $p = .05$. Additionally, chi-square tests revealed no significant differences between groups on concussion history, sport, sex, or occurrence of free or reduced lunch, again utilizing a significance level of $p = .05$. However, those athletes with positive implicit memory ratios had significant higher scores on the PAQ-A, ($t = -2.284$, $p = .026$). Analyses were conducted both with and without those with positive implicit memory ratios.

4.2 Evaluation of Hypotheses

The following data represent results from the SRTT with respect to concussion history and PA, exploring hypotheses 1 through 3. After reviewing the data, it became apparent that after the first block, many of the participants failed to reach the pre-determined 90 percent response accuracy criterion, and therefore only the first block was examined, yielding the following results from multiple regression analyses. The first results presented are from the entire sample of 64 athletes. Next, those athletes who failed to meet the response accuracy criterion were removed from analysis, resulting in 58 total participants, 17 with a history of concussion and 41 with no history of concussion. Finally, analyses were conducted after removing those participants who failed to reach the 90 percent response accuracy criterion and had positive implicit memory ratios, leaving 51 participants, 14 with a history of concussion and 34 with no history of concussion.

Serial Reaction Time Task Results (Hypotheses 1 – 3).

Behavioral results from the SRTT were used to explore the following specific aims and hypotheses, first with the entire sample of 64 participants. Follow-up analyses explored the specific aims and hypotheses with only the participants with 90 percent response accuracy and negative implicit memory ratios.

Specific Aim #1: Determine the relationship between concussion history (i.e., no previous concussion, one or more previous concussion(s)) and implicit memory acquisition in adolescents.

Hypothesis 1: Concussion history would be inversely related to implicit memory acquisition.

A linear regression analysis was used to explain the variance in implicit memory acquisition in adolescents by concussion history. Sex, SES, race and ethnicity, and age were entered into the model, but as they were not significantly predictive of any variance, they were not entered into the following model. Concussion history was entered as an independent variable, with implicit memory as a dependent variable. Results for this model appear in Table 8. In the first model, concussion history did not significantly explain the variance in implicit memory, $F(1,63) = 1.2$, $p = .274$, adj. $R^2 = .003$, and therefore did not support hypothesis 1. A scatter plot exploring the relationship between concussion history and implicit memory can be seen in Figure 5. No difference was seen overall between those with and without a history of concussion on implicit memory.

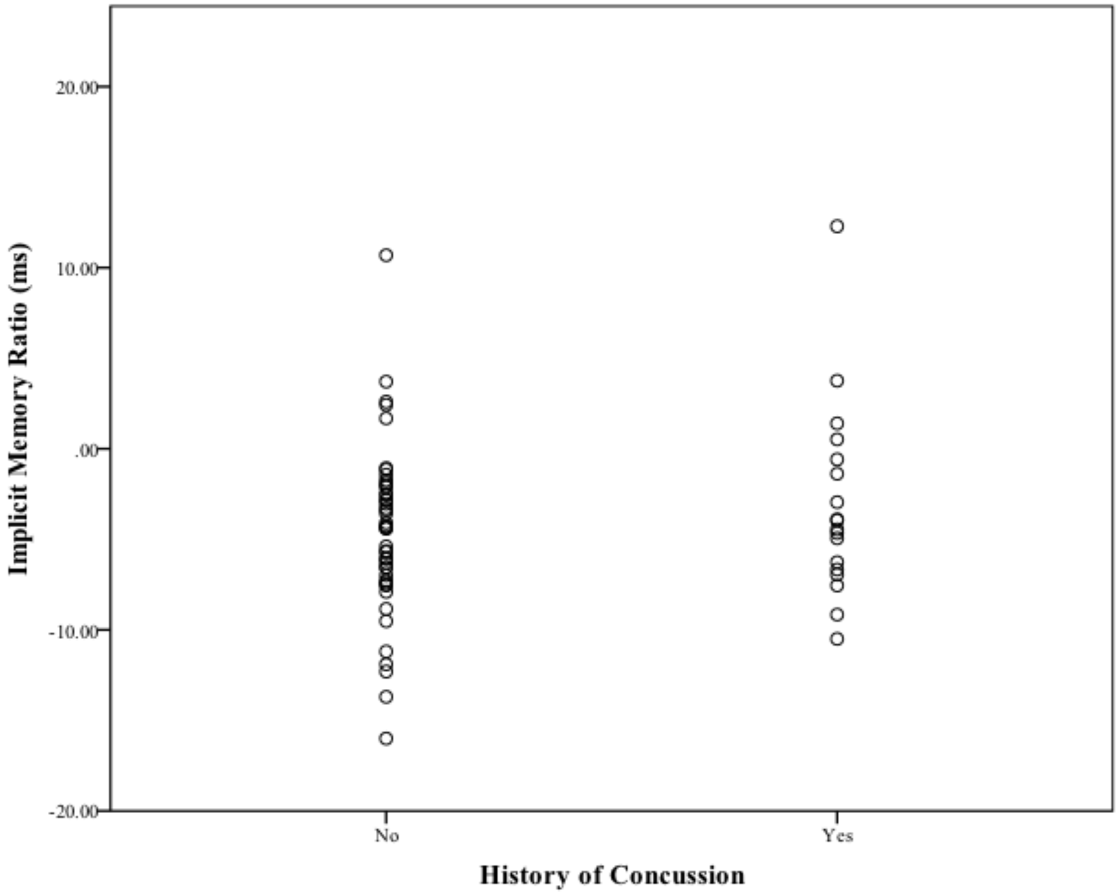

Figure 5. *Scatter plot exploring the relationship between a history of concussion and implicit memory (n = 64).*

Specific Aim #2: Determine the relationship between PA and implicit memory acquisition in adolescents.

Hypothesis 2: PA and implicit memory acquisition would be positively related.

Again, a linear regression analysis was executed to explore hypothesis 2. For the second model, the independent variable was PA with a dependent variable of implicit memory. PA did not significantly explain the variance in implicit memory in the second model, $F(1,59) = 1.1$, $p = .294$, adj. $R^2 = .002$, again failing to support hypothesis 2. Results for the second model appear in Table 8. A scatter plot exploring the relationship between PA and implicit memory can be seen in Figure 6, demonstrating no significant relationship between PA and implicit memory.

Table 8.

Results of Two Regression Analyses to Predict Implicit Memory from Concussion History and PA

	ß	R^2	Adj. R^2	*F*	*p*
1. Concussion History[a]	.139	.019	.003	1.216	.274
2. Physical Activity[b]	.138	.019	.002	1.123	.294

Note:
ß = standardized coefficient
[a]n = 64
[b]n = 60

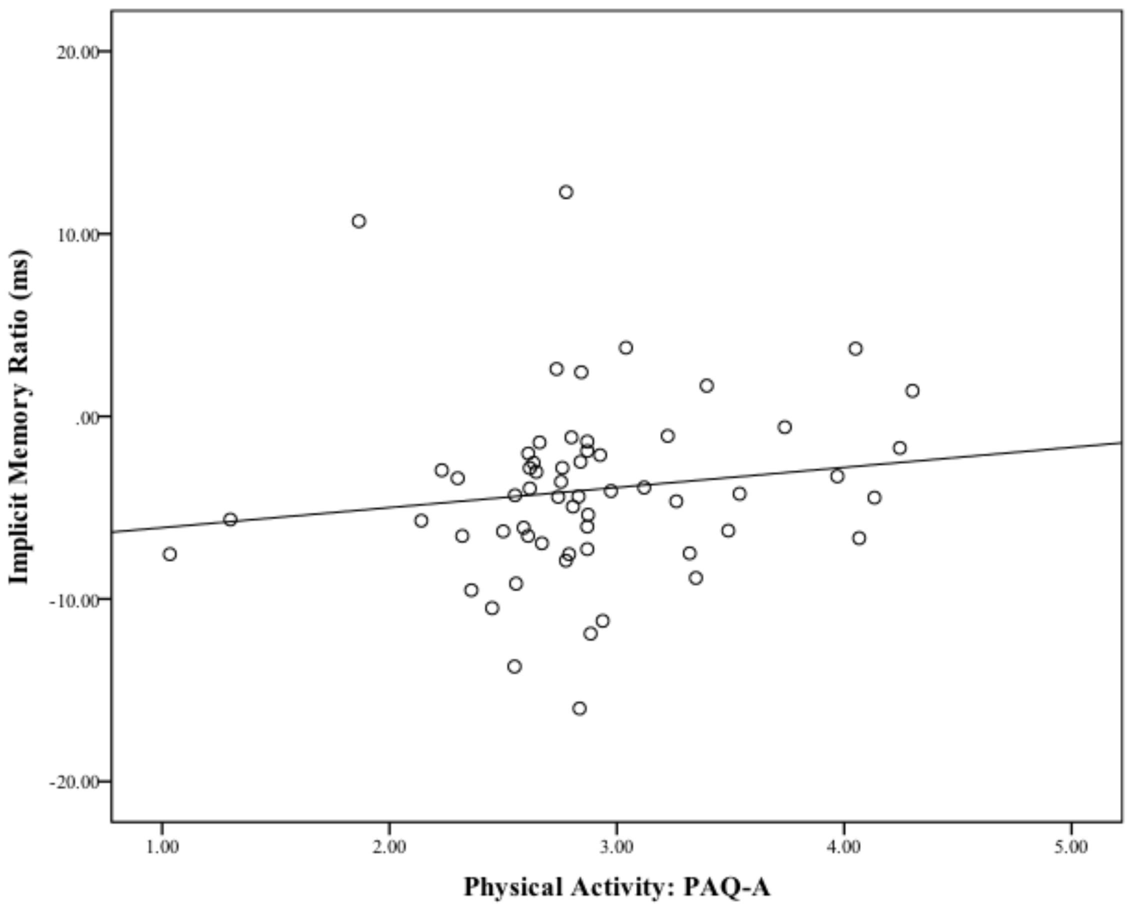

Figure 6. Scatter plot exploring the relationship between PA and implicit memory (n = 60).

Specific Aim #3: Examine the potential interaction between current level of PA and concussion history on implicit memory acquisition in adolescents.

Hypothesis 3: PA would protect against concussive effects on implicit memory acquisition.

Finally, a multiple regression analysis was used to explore the third hypothesis. The third model included the interaction between concussion history and PA, and was not significant, F(3,57) = .650, p = .586, adj. R^2 = .019. These results failed to support hypothesis 3. Regression coefficients and standard errors can be found in Table 9.

Table 9.

Results of Multiple Linear Regression using Concussion History and PA to Predict Implicit Memory Acquisition in Adolescents (n = 60)

	β	$SE_β$	ß	p
Intercept	-6.808	3.326		
Concussion History	-2.648	5.554	-.235	.636
Physical Activity	.898	1.165	.111	.444
Concussion_PA	.962	1.504	.322	.525

Notes:
Overall model not significant $F(3,57)$ = .650, p = .586, adj. R^2 = .019
β = unstandardized regression coefficient; $SE_β$ = standard error of the coefficient;
ß = standardized coefficient

A scatter plot exploring the interaction between concussion history and PA level can be seen in Figure 7. In order to assess the relationship between concussion history and implicit memory across levels of PA, PA was divided into three subsets of low, moderate, and high PA, based on scores on the PAQ-A from the current sample. The bottom tertile of participants were grouped into low PA, likewise the middle tertile of participants were categorized as moderate PA, and the highest tertile of participants were considered high PA. Figure 7 shows the resulting implicit memory ratios did not vary based on concussion history across levels of PA.

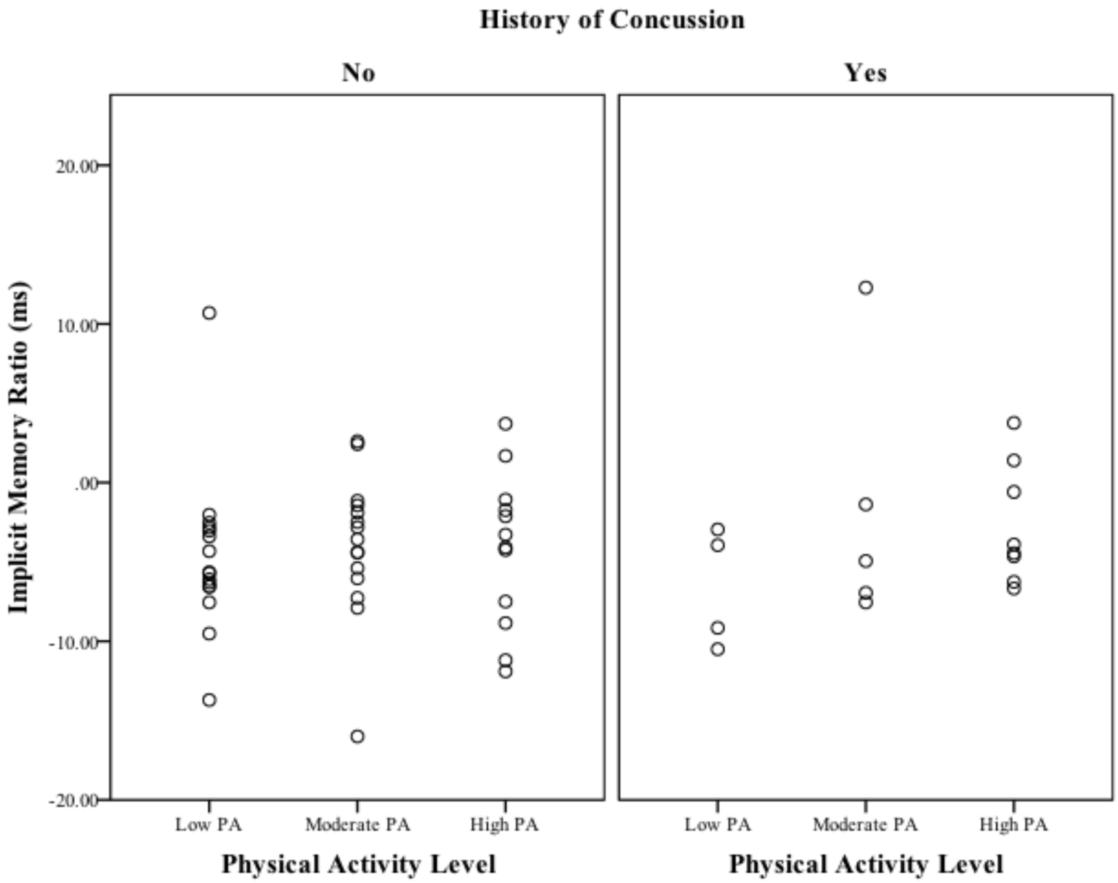

Figure 7. Scatter plot exploring the interaction between concussion history and PA level on implicit memory (n = 60).

The above analyses were conducted again utilizing only those participants who reached the 90 percent response accuracy criterion on the SRTT. The results of the first two regression analyses exploring the relationships between concussion history and implicit memory and PA and implicit memory can be found in Table 10. The effect of concussion history on implicit memory remained not significant, $F(1,57) = .678$, $p = .414$, adj. $R^2 = .006$. When those participants who failed to reach the 90 percent response accuracy criterion were removed, the effect of PA on implicit memory became significant, $F(1,54) = 5.545$, $p = .022$, adj. $R^2 = .078$, accounting for approximately 7.8 percent of the variance in implicit memory.

Table 10.

Results of Two Regression Analyses to Predict Implicit Memory from Concussion History and PA

	ß	R^2	Adj. R^2	*F*	*p*
1. Concussion History[a]	.109	.012	.006	.678	.414
2. Physical Activity[b]	.308	.095	.078	5.545	.022*

Notes:
*Significant at $p < .05$
ß = standardized coefficient
[a]n = 58
[b]n = 55

Scatter plots exploring the relationships between concussion history and implicit memory and PA and implicit memory can be found in Figures 8 and 9, respectively. Again, there was no difference on implicit memory between concussion history groups. Figure 9 demonstrates a linear relationship between scores on the PAQ-A and the implicit memory ratio. As this relationship is positive, it signifies that when PA was higher, the implicit memory ratio score became higher. Positive values indicated the average RT for sequence trials was longer than the average RT for random trials, which would indicate a lack of implicit learning. Therefore, the relationship suggests as current PA became higher, implicit learning may have been lower in adolescents.

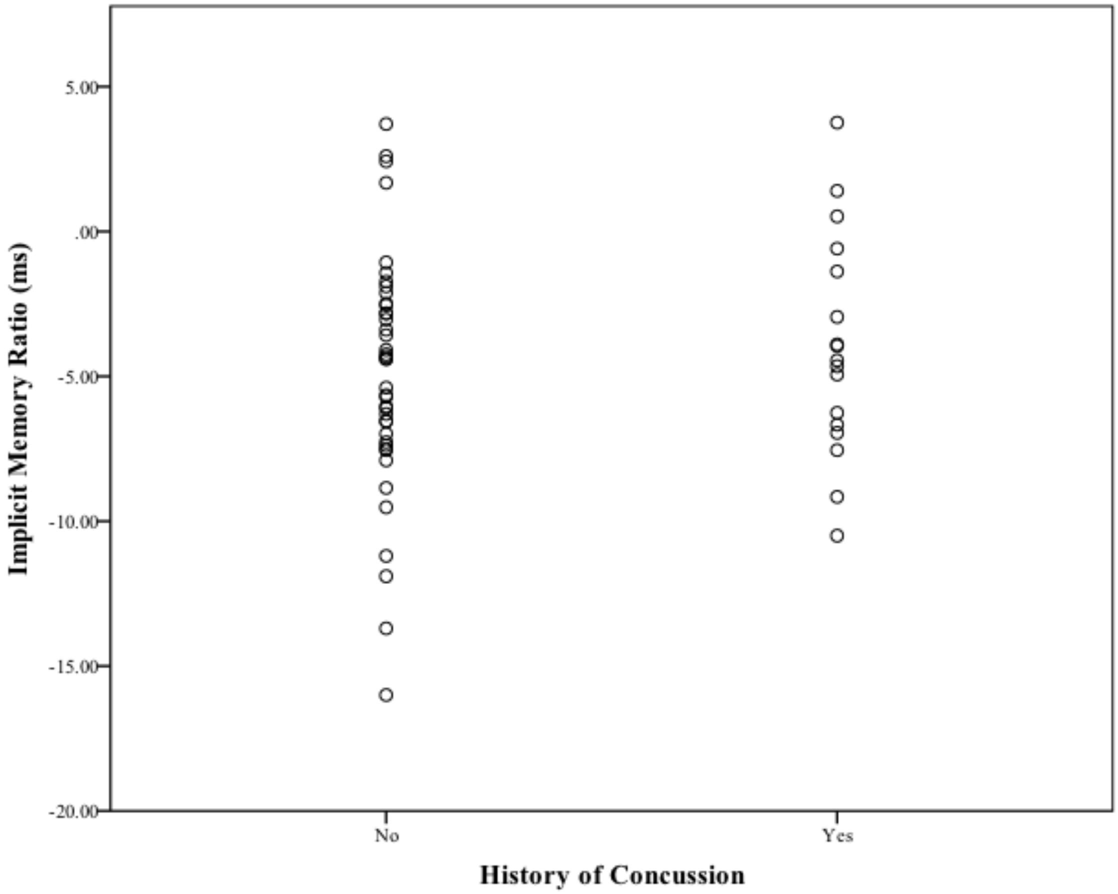

Figure 8. *Scatter plot exploring the relationship between concussion history and implicit memory (n = 58).*

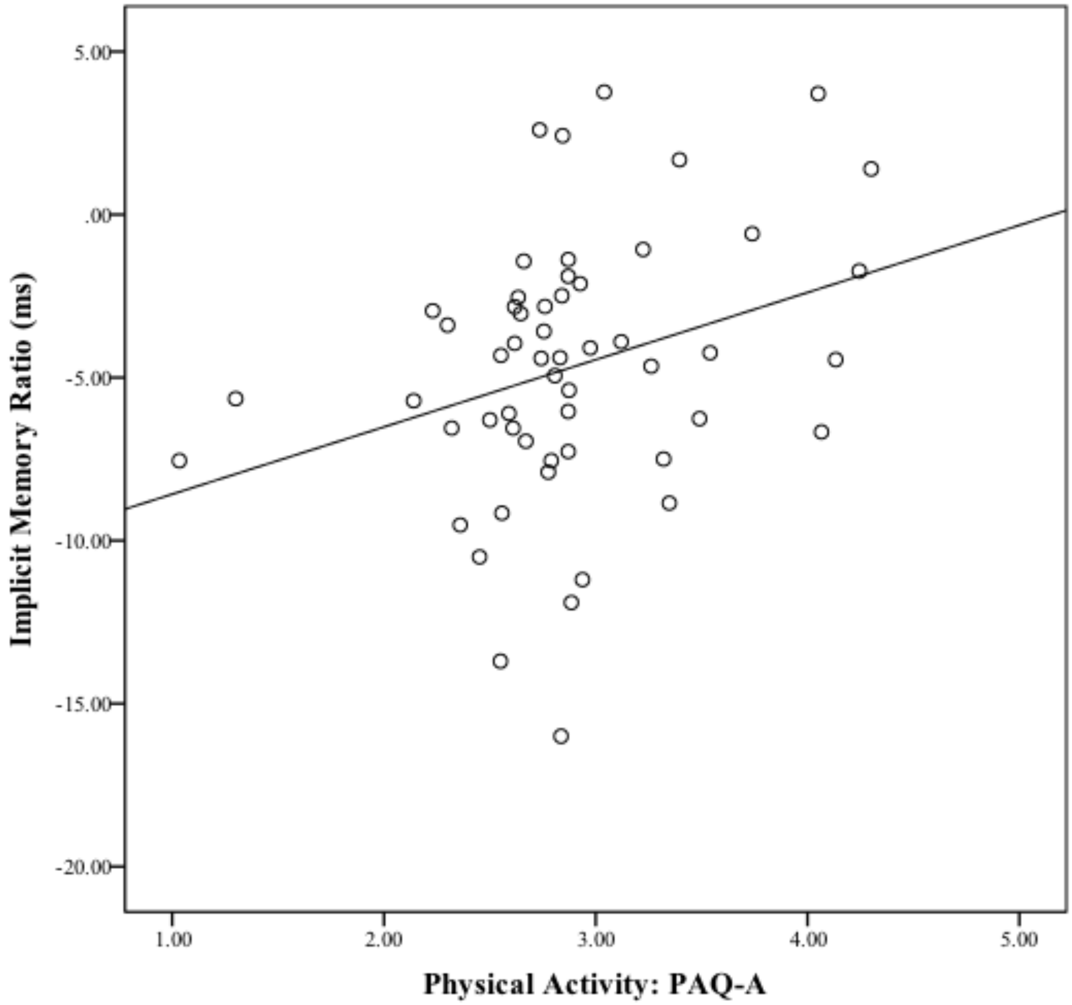

Figure 9. Scatter plot exploring the relationship between PA and implicit memory (n = 55).

The interaction was again analyzed using only those participants who had a response accuracy on the SRTT of at least 90 percent. Results from this multiple regression analysis can be found in Table 11. The overall model was significant, $F(3,52) = .3.023$, $p = .038$, adj. $R^2 = .104$. While the interaction term itself was not significant, the combination of all variables was significant. A scatter plot exploring the interaction between concussion history and PA on implicit memory in adolescents can be found in Figure 10. The scatter plot reveals no significant interaction between concussion history and PA on implicit memory in adolescents.

Table 11.

Results of Multiple Linear Regression using Concussion History and PA to Predict Implicit Memory Acquisition in Adolescents (n = 55)

	β	$SE_β$	ß	*p*
Intercept	-10.165	2.763		
Concussion History	-7.393	4.540	-.797	.110
Physical Activity	1.910	.970	.280	.055
Concussion_PA	1.969	1.212	.812	.111

Notes:
Overall model significant $F(3,52) = 3.023$, $p = .038$, adj. $R^2 = .104$
β = unstandardized regression coefficient; $SE_β$ = standard error of the coefficient;
ß = standardized coefficient

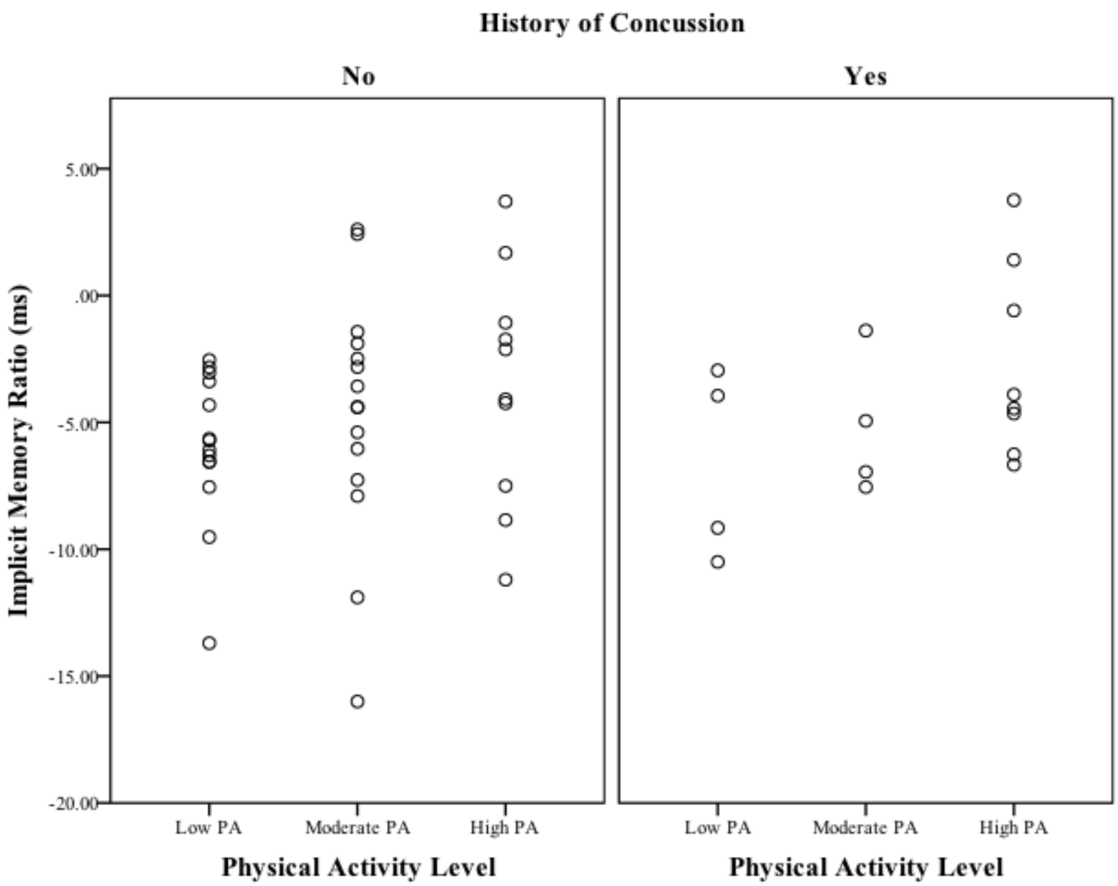

Figure 10. Scatter plot exploring the interaction between concussion history and PA on implicit memory (n = 55).

Finally, all regression analyses were once more conducted with only those participants with at least 90 percent response accuracy on the SRTT and with negative implicit memory scores, indicating implicit learning had occurred. Results from the two regression analyses exploring the effects of concussion history and PA on implicit memory can be found in Table 12. Neither concussion history nor PA significantly predicted any variance in implicit memory once removing those who did not meet the 90 percent response accuracy criterion and those with positive implicit memory scores.

Table 12.

Results of Two Regression Analyses to Predict Implicit Memory from Concussion History and PA

	ß	R^2	Adj. R^2	*F*	*p*
1. Concussion History[a]	.071	.005	.015	.250	.619
2. Physical Activity[b]	.178	.032	.011	1.543	.220

Note:
ß = standardized coefficient
[a]n = 51
[b]n = 49

Scatter plots demonstrating the relationships between concussion history and implicit memory and PA and implicit memory appear in Figures 11 and 12, respectively. These figures indicate there was no difference in implicit memory between concussion history groups. Additionally, there was no association between PA and implicit memory.

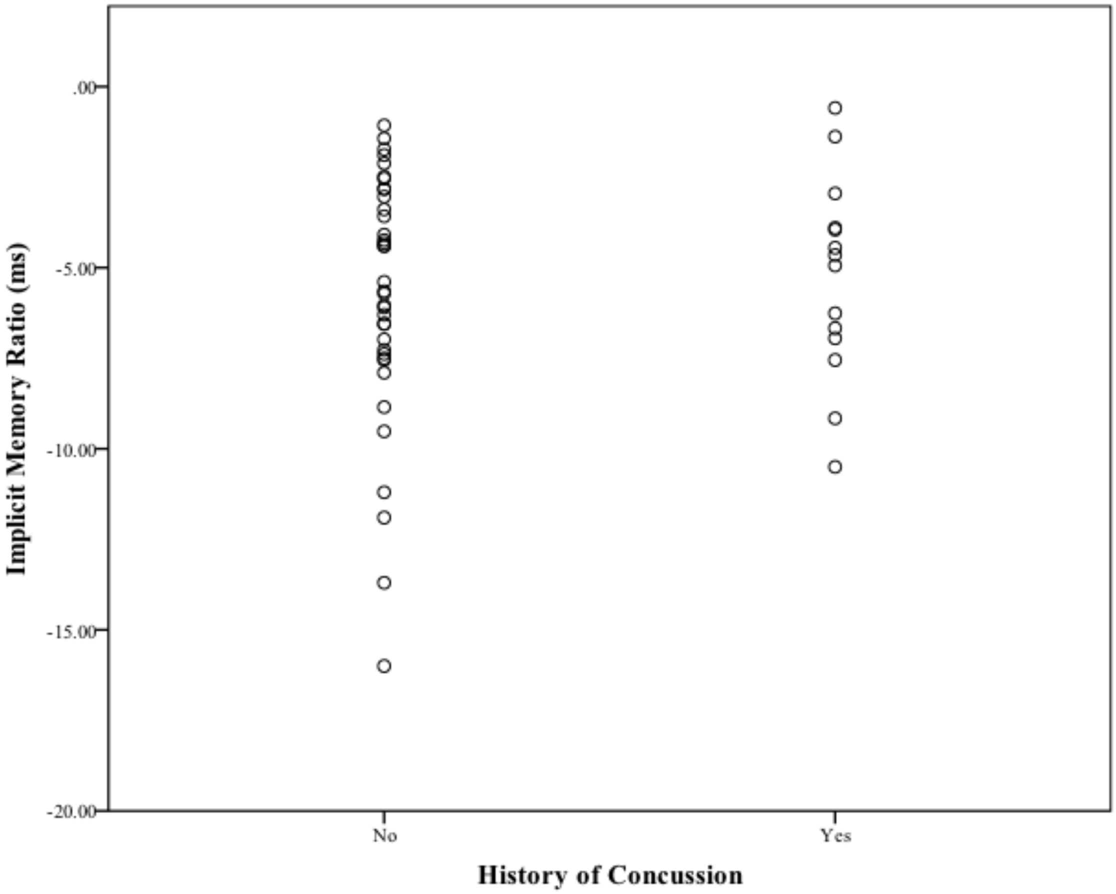

Figure 11. *Scatter plot exploring the relationship between concussion history and implicit memory (n = 51).*

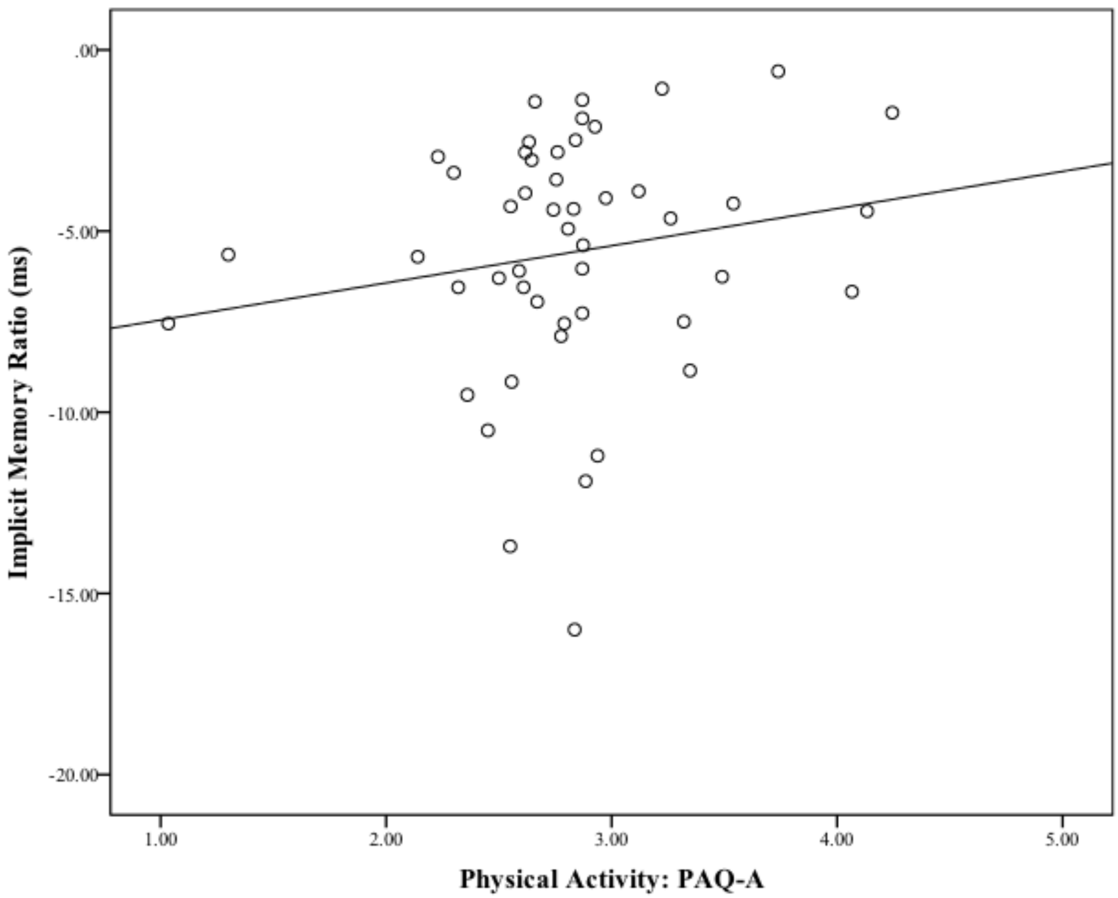

Figure 12. Scatter plot exploring the relationship between PA and implicit memory (n = 49).

The interaction between concussion history and PA and the impact on implicit memory was once more explored using a multiple linear regression after removing those participants with positive implicit memory ratios. Results from this analysis appear in Table 13. The overall model was not significant at predicting any variance in implicit memory, $F(3,46) = 1.028$, $p = .390$, adj. $R^2 = .002$. The scatter plot exploring this interaction can be found in Figure 13. This figure revealed no significant interaction between concussion history and level of PA.

Table 13.

Results of Multiple Linear Regression using Concussion History and PA to Predict Implicit Memory Acquisition in Adolescents (n = 49)

	β	$SE_β$	ß	*p*
Intercept	-8.387	2.603		
Concussion History	-4.315	4.155	-.565	.305
Physical Activity	.982	.934	.167	.299
Concussion_PA	1.212	.1.155	.583	.300

Notes:
Overall model not significant $F(3,46) = 1.028$, $p = .390$, adj. $R^2 = .002$
β = unstandardized regression coefficient; $SE_β$ = standard error of the coefficient;
ß = standardized coefficient

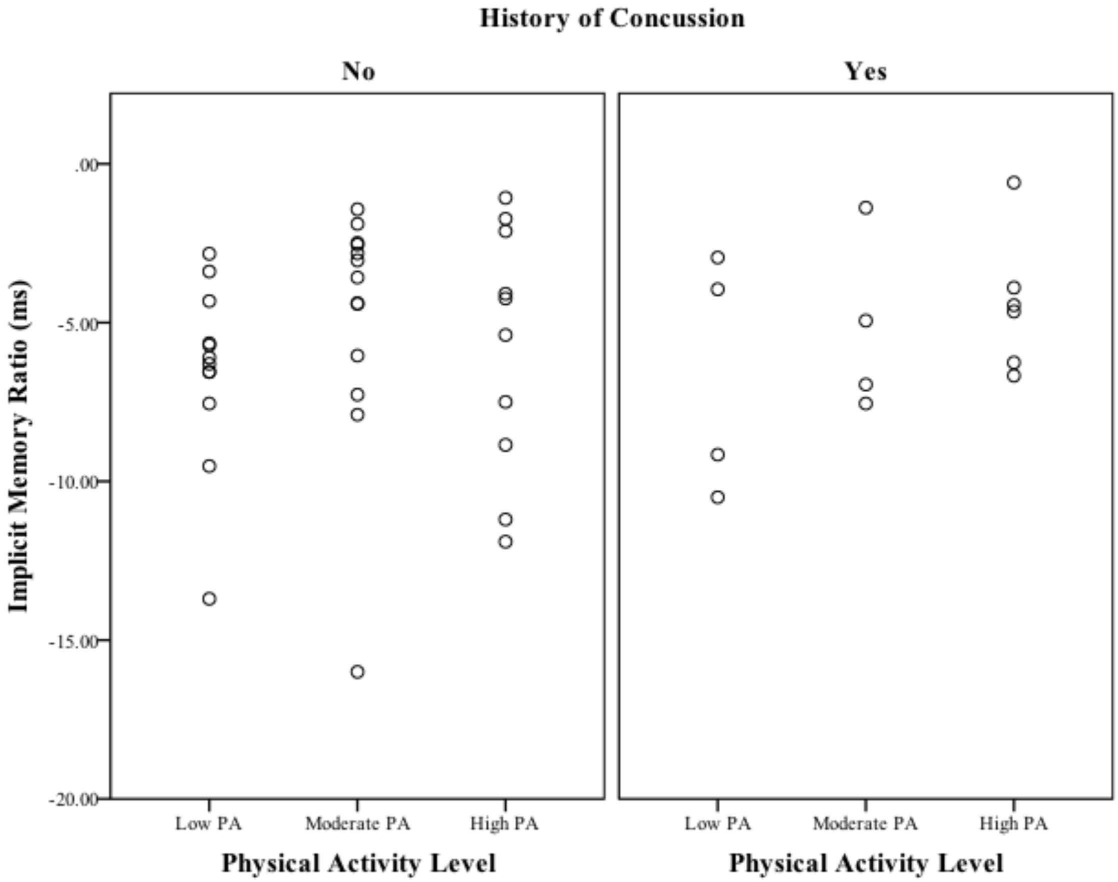

Figure 13. Scatter plot exploring the interaction between PA level and concussion history on implicit memory (n = 49).

CHAPTER 5

DISCUSSION

5.1 Introduction

This chapter discusses the results found in the current study and explores them in relation to the current literature on sport-related concussion and PA. First, the findings exploring implicit memory acquisition across concussion history groups are reviewed. Second, the results from the SRTT exploring the association between PA and implicit memory are reviewed. Third, the interaction between concussion history and PA on implicit memory acquisition was discussed. Finally, implications and suggestions for future research are proposed.

5.2 General Discussion of the Results

The purpose of the current study was to explore implicit memory acquisition in adolescents with and without a history of concussion and across varying levels of current PA. These associations were explored with the entire sample of 64 participants, as well as in reduced samples removing athletes who failed to reach a response accuracy threshold and who had positive implicit memory ratios. Concussion history was not associated with implicit memory acquisition in adolescents in the entire sample, as well as in the reduced samples. PA was significantly associated with implicit memory acquisition in adolescents, but only in the reduced sample including only those participants with a 90 percent response accuracy. Once those athletes with positive implicit memory ratios were removed, the relationship was no longer statistically significant. The relationship between current PA and implicit memory ratio was positive, meaning as PA was higher, the implicit memory ratio was also higher, demonstrating less implicit learning. The implicit memory ratio subtracted the mean RT of the random trials from the mean RT of the sequential trials; therefore a higher score indicated a slower RT on the sequence trials, or less implicit learning. The model including the interaction term between concussion history and current PA was significant in the reduced sample after removing those participants who failed to reach 90 percent response accuracy; however, the interaction term itself was not significant.

Many athletes (n = 6) failed to reach a 90 percent response accuracy criterion, limiting the use of their data. The response accuracy criterion was set at 90 percent on the SRTT based on previous literature using a similar threshold (Pontifex, et al., 2014). Participants needed to respond accurately at least 90 percent of the time for their data to be used in analysis. Performance resulting in response accuracy below this threshold was removed from subsequent analysis, as a low response accuracy limits the ability of the SRTT to measure implicit memory. Participants who fail to answer correctly at least 90 percent of the time may be assumed to not be actively participating in the task and as such would be randomly choosing the response, thus no implicit learning would take place. Because of the poor performance across subsequent blocks, only the first block was analyzed. Furthermore, many participants had a positive RT ratio, indicating no implicit learning had actually taken place so early in the task. Thus, performance on the SRTT was likely not optimal.

The poor performance could be explained by many different factors including a lapse in attentional focus and a lack of intrinsic motivation. Previous research suggests it is not uncommon for momentary lapses in attention to occur (Sonuga-Barke & Castellanos, 2007; Weissman, Roberts, Visscher, & Woldorff, 2006). Furthermore, these attentional lapses have been demonstrated to impair the individual's ability to minimize distraction (Weissman, et al., 2006), which may be particularly relevant for the athletes in the current study. Many of these athletes were completing the SRTT in a room with their teammates or friends. With this knowledge in attentional focus, it is possible the athletes in the current study endured momentary lapses in attention or were unable to minimize distractions, resulting in poorer performance.

Furthermore, the athletes in the current study may not have found the task intrinsically motivating. Previous research suggests an individual will only be intrinsically motivated for those activities that provide interest for them (Ryan & Deci, 2000). Thus, the athletes in the current study may have found little interest, challenge, or value in the task, leaving them little intrinsic motivation to perform the task at their highest abilities.

In measuring an adolescent population, results may have been affected by puberty and brain development that occur during this time period. During adolescence, the brain undergoes a structural reorganization, in which white matter increases and gray matter peaks and then begins to decrease. White matter typically increases in a predominantly linear pattern (Blakemore & Choudhury, 2006; Blakemore, Burnett, & Dahl, 2010). Given white matter increases at a steeper rate in males than females, it has been suggested that testosterone may be responsible for the relationship between age and white matter volume (Blakemore & Choudhury, 2006). Because white matter is typically a representation of myelinated axons on MRI scans, the increase in white matter is typically seen as an increase in axonal myelination (Blakemore & Choudhury, 2006). Gray matter changes in a non-linear manner in somewhat of an inverted-U shape. Initially, gray matter increases in the brain during childhood, but then reaches a peak in adolescence, plateaus, and decreases through adulthood (Blakemore, et al., 2010; Blakemore & Choudhury, 2006). The peaks in gray matter often occur in unison with the onset of puberty, suggesting a possible interaction between hormones and gray matter development (Blakemore & Choudhury, 2006; Sisk & Zehr, 2005). The interaction between white and gray matter volume suggests the peak of gray matter at puberty represents an increase in the number of synapses in the brain, followed by reorganization during puberty in which synaptic pruning takes place, followed by an increase in axonal myelination (Blakemore & Choudhury, 2006; Sisk & Zehr, 2005).

Both the synaptic pruning and axonal myelination increase efficiency of information processing (Steinberg, 2005). These changes in white and gray matter volume are influenced by steroid hormone changes related to puberty and development (Sisk & Zehr, 2005). As adolescents of the same chronological age may be at different pubertal stages, a measure of age alone may not capture what is occurring in the brain during adolescence (Blakemore, et al., 2010). Previous studies have demonstrated differences in executive functioning and cognitive behavior before, during, and after puberty, suggesting a measure of pubertal status may aid in interpreting differences in implicit memory in adolescents (Blakemore & Choudhury, 2006). Furthermore, pubertal status could influence the brain's vulnerability to concussive effects. As no research to date has explored this possibility, it is difficult to predict whether any potential interaction between concussion and pubertal status is concentrated with the pre- versus post-pubertal adolescents.

Findings may have also been influenced by the particular sport in which the athlete was participating. However, current sport was not utilized as a covariate to attempt to eliminate any undue influence, as the majority of athletes reported participating in multiple sports. Furthermore, while whether or not the athlete was in-season or out-of-season may have also contributed to the results, the majority of out-of-season athletes were participating in off-season conditioning. Additionally, while age and sex have previously been demonstrated to affect cognitive tasks, the current study used these variables as covariates and found no significant differences.

Overall, the findings suggested a history of concussion is not associated with implicit memory acquisition in adolescents. However, current PA may have been associated with performance on the SRTT in the reduced sample. Additionally, adding the interaction term between concussion history and PA increased the significance of the overall model in predicting implicit memory. These findings, however, should be taken into consideration with the above-mentioned performance discrepancies, as well as the developmental changes occurring in adolescence. The current study's results will be discussed in greater detail and in relation to existing literature regarding sport-related concussion and PA.

5.3 Concussion History

The results from the current study indicated concussion history had no significant association with implicit memory acquisition in adolescents. More specifically, athletes with a history of concussion showed no significant differences on SRTT measures of implicit memory acquisition, compared to athletes with no history of concussion. However, given the limitations of the current study, including the limited sample size, the relationship between concussion history and implicit memory should be more fully explored.

The present study's findings are in contrast to findings by De Beaumont and colleagues (2012; 2013) that supported prolonged decrements in implicit memory after concussion in adults. De Beaumont et al. (2012) found university athletes with a history of two or more concussions demonstrated prolonged deficits in implicit memory acquisition on the SRTT, as compared to university athletes with no history of concussion. Similar findings were demonstrated by De Beaumont and colleagues (2013) where retired university athletes with a history of one of more concussion(s) continued to display markedly reduced implicit motor learning compared to those retired athletes with no history of concussion. These researchers concluded there might be impairment in implicit memory as a result of previous concussion(s), even when the symptoms have been resolved for many years (i.e., average time since last concussion of 37 years).

Previous researchers have suggested long-term effects of concussion on memory (Covassin, et al., 2010; Iverson, et al., 2012; Iverson, et al., 2004; Guskiewicz, et al., 2005). Covassin and colleagues (2010) demonstrated poorer visual and verbal memory performance in those athletes with a history of multiple concussions compared to athletes with no history of concussion. Similarly, Iverson et al. (2012) found athletes between 17 and 22 years old, with a history of three or more concussions, performed significantly worse on verbal memory than matched controls with no history of concussion. Furthermore, in a study with both high school and collegiate athletes, Iverson et al. (2004) found athletes with a history of three of more concussions performed significantly worse on memory tasks at baseline than matched controls with no history of concussion. Additionally, Guskiewicz and colleagues (2005) specifically explored memory in retired football players. The findings indicated those athletes with a history of three or more concussions had a threefold prevalence of significant memory problems. The results from these previous studies suggest a history of concussion may result in long-term memory (i.e., 3 to 5 years in Covassin, et al., 2010) impairments; however, implicit memory was not tested.

The contrast in findings between the current study and the research done by De Beaumont and colleagues may be attributed in part to the age of the participants. In one study, De Beaumont et al. (2012) explored implicit memory acquisition in university athletes, aged 19 to 27 years old (mean age = 23.4 years). In 2013, De Beaumont et al. tested retired university athletes, aged 51 to 75 years old (mean age = 60.87 years). The current study examined implicit memory acquisition in adolescents, aged 14 to 19 years, (mean age = 16.40 years). Given the differences in age, the current study suggests the adolescent brain may not demonstrate the same relationship between concussion history and implicit memory. As previously discussed, during this time in adolescence, the brain is undergoing numerous changes in gray and white matter volume and reorganization of the synapses, which may influence the way the brain responds to a concussion. Additionally, while many previous studies have demonstrated long-term memory effects (i.e., 3 to 5 years) of concussion (Covassin, et al., 2010; Iverson, et al., 2012; Iverson, et al., 2004; Guskiewicz, 2005), the current study did not show a similar association in implicit memory, suggesting that while working memory and explicit memory may be affected by concussion, it is possible concussions may not be associated with the implicit memory system, at least in adolescents with a history of one of more concussion(s). Previous research examining implicit memory after moderate to severe brain injury in children and adolescents may hold relevance to the current study's findings (Lah, et al., 2011; Shum, et al., 1999; Ward et al., 2004; Ward et al., 2002).

The current findings fall in line with the implicit memory research in children and adolescents following moderate to severe brain injury (Shum, et al., 1999; Ward et al., 2004; Ward et al., 2002). Shum et al. (1999) demonstrated no differences in implicit memory between a non-injured group of controls, and children who had sustained a severe brain injury at least one year prior, demonstrated by performance on a picture completion task. The study tested children aged 4 to 14 years (mean age = 8.4 years). Furthermore, Ward et al. (2002) showed similar findings in children aged 8 to 15 years (mean age = 9.5 years). No difference was seen between the injured group, who had sustained a moderate or severe brain injury at least six months prior, and the control group on the rotary pursuit task and the mirror reading task, demonstrating intact implicit memory (Ward, et al., 2002). Furthermore, Ward and colleagues (2004) interviewed parents of children who had sustained a brain injury ranging from mild to severe and found no suggestion of deficits in implicit memory. These studies, coupled with the current study, suggest brain injury in the child and adolescent brain may not be associated with implicit memory.

The results from previous researchers (i.e., Shum et al. (1999); Ward et al. (2002; 2004)), and the current study indicate there are no prolonged deficits (i.e., at least 6 months to one year since injury) in implicit memory acquisition in children and adolescents following brain injury. However, these findings should be taken with caution, as De Beaumont and colleagues (2012; 2013) have demonstrated the potential for long-term effects (up to 37 years) on implicit memory following concussion in an adult population. Furthermore, given the current study grouped all previous concussions in one group, it is possible the relationship between implicit memory and concussion history may not be discernable after one previous concussion, but require a history of two or more concussions. Previous research has demonstrated many of the long-term effects of concussion follow a dose-response relationship (Covassin, et al., 2010; Iverson, et al., 2012; Iverson, et al., 2004; Master, et al., 1999; Moser & Schatz, 2002; Moser, et al., 2005; Master, Kessels, Lezak, & Troost, 2010; Schatz, et al., 2011; Guskiewicz, et al., 2005). Additionally, the sample in the current study had multiple limitations including low response accuracy and positive implicit memory ratios.

5.4 Physical Activity

The results of the current study demonstrated PA was statistically significant in explaining some variance in implicit memory scores on the SRTT in adolescents, when exploring the reduced sample size, but not when excluding individuals with a positive implicit memory ratio. Furthermore, there was a positive relationship between PA and implicit memory ratios, suggesting higher levels of current PA results in higher implicit memory ratios. This positive relationship is contrary to what was expected, as higher implicit memory ratios indicate less or no implicit learning. Because this relationship was no longer present after removing those individuals with positive implicit memory ratios, it is difficult to ascertain the true relationship between PA and implicit memory. Furthermore, previous t-tests revealed a significant difference between those individuals with positive implicit memory ratios and those with negative implicit memory ratios on scores on the PAQ-A. Athletes with positive implicit memory ratios scored significantly higher on the PAQ-A than athletes with negative implicit memory ratios, potentially influencing the results of the regression analyses.

Previous literature has demonstrated a significant effect of PA on cognition (Colcombe & Kramer, 2003; Sibley & Etnier, 2003; Smith et al., 2010; Fedewa & Ahn, 2011), showing overall a strong, positive relationship between PA and cognitive functioning. These results have been demonstrated via different tasks and across the lifespan. Some previous research has demonstrated an effect of PA on memory in children (Fisher, et al., 2011; Chaddock, et al., 2010). Fisher and colleagues (2011) found those children (mean age = 6.2 years; SD = 0.3) involved in an exercise intervention performed significantly better on tests of spatial working memory. Specifically, those children involved in the 10-week exercise intervention group were to perform significantly better on the spatial working memory errors subscales of the Cambridge Neuropsychological Test Battery compared to controls. Additionally, Chaddock et al. (2010) showed higher-fit children (mean age = 10.0 years; SD = 0.6) had larger bilateral hippocampal volume and performed better on relational memory tasks than lower-fit children. However, no literature to date has explored PA and its specific relationship with implicit memory in adolescents, the current study excluded.

One earlier study particularly looked at the relationship between aerobic fitness on implicit memory in college students (Pontifex, et al., 2014) and found those participants with poorer aerobic fitness, as measured by VO_2 max, demonstrated lower implicit memory on the SRTT. The findings are in contrast to the current study that found a possible negative relationship between current PA and implicit memory. It is of importance, however, that while PA and aerobic fitness are related, they are considered separate entities, and therefore the results cannot be completely compared between the two studies. Furthermore, the study by Pontifex and colleagues (2014) examined college-aged students (mean age = 20.2 years; SD = 2.2), who were not necessarily athletes, while the current study explored high-school aged athletes, which may account for some differences. Developmental changes in the brain during adolescence make the two populations difficult to compare directly. Furthermore, using high school athletes may have supplied a more physically active sample than non-athlete, college students, although PA information was not collected on the previous study.

Previous research has demonstrated a positive relationship between PA and cognition across the lifespan (Colcombe & Kramer, 2003; Sibley & Etnier, 2003; Smith et al., 2010; Fedewa & Ahn, 2011; Fisher, et al., 2011; Chaddock, et al., 2010; Pontifex, et al., 2014). Given the current findings suggesting an increase in current PA may be related to lower implicit learning, future studies should be conducted exploring this relationship, specifically given the limitations of including those athletes with positive implicit memory ratios. Positive implicit memory ratios indicate no implicit learning has occurred. After removing those individuals, the relationship between PA and implicit memory was no longer significant. Furthermore, significant differences in PAQ-A scores were noted between those with positive and those with negative implicit memory ratios.

5.5 Interaction Between Concussion History and Physical Activity

The overall model including the interaction between concussion history and current PA on implicit memory in adolescents was significant in predicting variance in implicit memory acquisition, although the interaction term itself was not statistically significant. When more closely examining the interaction, the relationship between PA and implicit memory did not vary across concussion history groups (i.e., no history of concussion, one or more concussion(s)). While it was hypothesized that the relationship between concussion history and implicit memory would vary across PA based on the theory of cognitive reserve, the current study did not support these findings. Specifically, it was hypothesized that in physically active individuals, the brain may not only have a higher threshold for demonstrating marked effects of brain injury, but may also be more efficient at compensating for any deficiencies in injured areas of the brain (Stern, 2002; Stern, 2003; Stern, 2009). The inability for the current study to demonstrate this association may be in part due to the low variability in PA levels, given the study consisted entirely of athletes.

The current study employed high school athletes who may have represented a more active sample than the general population of high school students. In the current sample, the overall average PAQ-A score was 2.87 (SD = .59), whereas an earlier study utilizing the PAQ-A found the average PAQ-A score to be 2.31 (SD = .63), almost a full standard deviation lower than the average in the current study (Kowalski, et al., 1997). Furthermore, in the study by Kowalski, et al., the average score for males was 2.52 (SD = .66) and for females was 2.12 (SD = .53). The current study recorded an average score of 2.97 for males (SD = .54) and 2.77 for females (SD = .67); again, both groups were almost a standard deviation higher in the current study. Thus, the sample in the current study represents a more active population than the general high school population in previous studies.

Furthermore, the current study did not demonstrate a change in the relationship between PA and implicit memory across concussion history groups (i.e., no concussion, one or more previous concussion(s)). Again, these findings may not be representative entirely of no interaction effect, but rather a lack of athletes with a history of multiple concussions. Given previous research has noted a dose-response effect in the number of previous concussions on cognitive outcomes (Collins, et al., 2002; Covassin, et al., 2013; Eisenberg, et al., 2013; Guskiewicz, et al., 2003; Covassin, et al., 2008), it is possible an association was not recognized in the current study because athletes with any history of concussion were grouped together.

5.6 Implications of Findings

Currently, sport-related concussion is an important topic, both in the medical field and in clinical settings. There remains an on-going debate regarding the long-term and cumulative effects of concussions. While the general findings in the current study suggest there may not be an association between concussions and implicit memory acquisition in the adolescent brain, previous research suggesting long-term neurocognitive effects should not be ignored. Specifically, previous research has demonstrated long-term effects (i.e., 3 to 5 years post-injury) on memory in adolescents, excepting implicit memory. Furthermore, long-term impairments (i.e., 37 years post-injury) have been noted in adults with a history of concussion on implicit memory. However, some previous research has noted no measureable differences on cognitive measures between those athletes with a history of concussion and those without (Broglio, et al., 2006; Bruce & Echemendia, 2009; Collie, McCrory, & Makdissi, 2006; Iverson, et al., 2006; Macciocchi, et al., 2001). The findings of the current study, however, should be considered under the circumstances and limitations in the sample size and utilizing only the first block of the SRTT.

Furthermore, the findings of the current study suggest PA level may possibly be associated with implicit memory acquisition in adolescents. Findings from the current study indicated an increase in current PA predicted lower implicit learning, only in those athletes with 90 percent response accuracy, and including those athletes with positive implicit memory scores. The current findings, however, relate to an active, adolescent population, specifically high school athletes. Thus, the impact of PA in adolescents should be further explored, including a more sedentary population. Furthermore, including those individuals with positive implicit memory ratios may have interfered with the true relationship between current PA and implicit memory, specifically noting those athletes with positive implicit memory ratios scored significantly higher on the PAQ-A.

5.7 Limitations

The current study was bound by certain limitations. First, the sample was one of convenience of local high school athletes, and as such may not be representative of the larger population. Furthermore, the small sample size made generalizability across the population difficult. In addition, concussion history was taken solely on the basis of self-report of the athletes, and therefore some athletes may have unknowingly sustained a concussion or failed to report a previous concussion. An athlete who may have unknowingly sustained a concussion may have been placed in the no concussion group, which may have influenced results. Additionally, given the limited number of athletes who had previously sustained multiple concussions, athletes who had sustained any number of concussions were grouped together, even though previous research suggests a possible dose-response with regard to the number of previous concussions (Collins, et al., 2002; Covassin, et al., 2013; Eisenberg, et al., 2013; Guskiewicz, et al., 2003; Covassin, et al., 2008). Moreover, no measure of pubertal status was obtained. Because previous research has demonstrated a direct relationship between puberty and brain development, the athletes' pubertal statuses may have influenced the variance in implicit memory. Furthermore, as previously discussed, many athletes failed to reach the 90 percent response accuracy threshold and as such were removed from analysis, again limiting the sample size.

Because of the low response accuracy, only the first block of the SRTT was utilized for analysis, potentially limiting the participants' implicit learning. Typically greater implicit learning will occur in later blocks of the SRTT, rather than the first block. Many of the participants had a positive RT ratio, indicating no implicit learning had occurred. With that in mind, it is difficult to ascertain the true relationships between PA and concussion history with implicit memory acquisition in adolescents.

5.8 Suggestions for Future Research

Future research should expand the sample size to potentially become more representative of the general population. By using a larger sample size the study may allow for further breakdown of concussion history into multiple groups (i.e., no previous concussion, one previous concussion, two previous concussions, three or more previous concussions) to explore the possibility of a dose-response on implicit memory. Additionally, future research may explore the use of non-athlete controls, to reduce the possibility of undiagnosed concussions, as well as allow for a potentially more sedentary sample. Future studies may consider testing athletes individually or in a lab setting, to reduce potential attentional lapses as a result of distraction.

Furthermore, future studies may explore using a measure of pubertal status, as well. If pubertal status is obtained, it may help to further explain any variance demonstrated in implicit memory.

5.9 Conclusions

While previous research has demonstrated deficits in implicit memory acquisition in previously concussed, asymptomatic adults, the current study did not replicate these results in an adolescent population. These findings suggest, in adolescents, concussions may not be associated with implicit memory acquisition. However, given the circumstances of the current study, including a small sample size reduced additionally by low response accuracy and positive implicit memory ratios, future work should more fully explore the possible relationship. Additionally, the current study demonstrated an association between current PA and implicit memory, suggesting PA might be negatively related to implicit learning in adolescents. This finding is contrary to previous studies, and given the limitations of the current study, specifically the inclusion of positive implicit memory ratio scores, should be further explored. Moreover, while the overall model including the interaction term between concussion history and PA relative to implicit memory was statistically significant, deeper exploration revealed no significant interaction between the two variables. This may be in part due to the lack of athletes with multiple concussions and the relatively active population sampled. In conclusion, the current results suggest concussions in adolescents may not be associated with implicit memory acquisition, but further studies are warranted given the circumstances and limitations of the current study. Furthermore, PA may have a negative association with implicit memory acquisition in an active, adolescent population; however, the previously mentioned limitations suggest more research must be conducted exploring this potential relationship before generalizations are indicated.

APPENDICES

APPENDIX A

Demographic Information Survey

Demographic Information

ID: ____

Age: __________ Sex: ☐ Male ☐ Female

Height: ________ Weight: _____________

Grade in School: _____________

Race or ethnicity:

- ☐ American Indian or Alaska Native
- ☐ Asian
- ☐ Black or African American
- ☐ Hispanic or Latino
- ☐ Native Hawaiian or Pacific Islander
- ☐ White
- ☐ Other
- ☐ I prefer not to answer

Approximate GPA:

- ☐ 2.5 or below
- ☐ 2.5-3.4
- ☐ 3.5-4.4
- ☐ 4.5 or above

Have you ever been part of the free/reduced lunch program?

- ☐ Yes
- ☐ No
- ☐ I prefer not to answer

Sport currently playing: ________________________________

Position in current sport: ______________________________

Years of experience in sport at the high school level:____________________

Other sports played within the last year: __________________________

Figure 14. Demographic Information Survey.

Figure 14 (cont'd)

Do you participate in organized sport year-round?:

- ☐ Yes
- ☐ No
- ☐ I prefer not to answer

Check any of the following that apply:

- ☐ Received speech therapy
- ☐ Attended special education classes
- ☐ Repeated one or more years of school
- ☐ Diagnosed learning disability

Indicate whether you have experienced the following:

- ☐ Treatment for headaches by physician
- ☐ Treatment for migraine headaches by physician
- ☐ Treatment for epilepsy/seizures
- ☐ Treatment for brain surgery
- ☐ Treatment for meningitis
- ☐ Treatment for substance/alcohol
- ☐ Treatment for psychiatric condition (depression/anxiety)

Have you ever been diagnosed with any of the following conditions?

- ☐ ADD/ADHD
- ☐ Dyslexia
- ☐ Autism

Have you participated in any strenuous exercise and/or exertion in the last 3 hours?

- ☐ Yes
- ☐ No

Hours of sleep last night: ___________________

Number of times diagnosed with a concussion by an athletic trainer or doctor:
____

Total number of concussions that resulted in loss of consciousness (i.e., blacked out):
____

Figure 14 (cont'd)

Total number of concussions that resulted in difficulty with memory for events occurring immediately after injury: _______________

Total number of concussions that resulted in difficulty with memory for events occurring immediately before injury: _____________

Total games missed as a direct result of all concussions combined: __________________________

Please list your five most recent concussions, if applicable (not including current concussion). Use approximate dates if necessary.

____ ____

____ ____

____

APPENDIX B

Physical Activity Questionnaire – Adolescents (PAQ – A)

We are trying to find out about your level of physical activity from ***the last 7 days*** (in the last week). This includes sports or dance that make you sweat or make your legs feel tired, or games that make you breathe hard, like tag, skipping, running, climbing, and others.

Remember:
There are no right and wrong answers — this is not a test.
Please answer all the questions as honestly and accurately as you can — this is very important.

1. Physical activity in your spare time: Have you done any of the following activities in the past 7 days (last week)? If yes, how many times? (Mark only one circle per row.)

	No	1-2	3-4	5-6	7 times or more
Skipping	☐	☐	☐	☐	☐
Rowing/canoeing	☐	☐	☐	☐	☐
In-line skating	☐	☐	☐	☐	☐
Tag	☐	☐	☐	☐	☐
Walking for exercise	☐	☐	☐	☐	☐
Bicycling	☐	☐	☐	☐	☐
Jogging or running	☐	☐	☐	☐	☐
Aerobics	☐	☐	☐	☐	☐
Swimming	☐	☐	☐	☐	☐
Baseball, softball	☐	☐	☐	☐	☐
Dance	☐	☐	☐	☐	☐
Football	☐	☐	☐	☐	☐
Badminton	☐	☐	☐	☐	☐
Skateboarding	☐	☐	☐	☐	☐
Soccer	☐	☐	☐	☐	☐
Street hockey	☐	☐	☐	☐	☐
Volleyball	☐	☐	☐	☐	☐
Floor hockey	☐	☐	☐	☐	☐
Basketball	☐	☐	☐	☐	☐
Ice skating	☐	☐	☐	☐	☐
Cross-country skiing	☐	☐	☐	☐	☐
Ice hockey/ringette	☐	☐	☐	☐	☐
Other: ____________________	☐	☐	☐	☐	☐

Figure 15. Physical Activity Questionnaire – Adolescents (PAQ – A)

Figure 15 (cont'd)

2. In the last 7 days, during your physical education (PE) classes, how often were you very active (playing hard, running, jumping, throwing)? (Check one only.)

- I don't do PE .... ☐
- Hardly ever .... ☐
- Sometimes .... ☐
- Quite often .... ☐
- Always .... ☐

3. In the last 7 days, what did you normally do *at lunch* (besides eating lunch)? (Check one only.)

- Sat down (talking, reading, doing schoolwork)....... ☐
- Stood around or walked around .... ☐
- Ran or played a little bit .... ☐
- Ran around and played quite a bit .... ☐
- Ran and played hard most of the time .... ☐

4. In the last 7 days, on how many days *right after school*, did you do sports, dance, or play games in which you were very active? (Check one only.)

- None .... ☐
- 1 time last week .... ☐
- 2 or 3 times last week .... ☐
- 4 times last week .... ☐
- 5 times last week .... ☐

5. In the last 7 days, on how many *evenings* did you do sports, dance, or play games in which you were very active? (Check one only.)

- None .... ☐
- 1 time last week .... ☐
- 2 or 3 times last week .... ☐
- 4 or 5 last week .... ☐
- 6 or 7 times last week .... ☐

6. *On the last weekend*, how many times did you do sports, dance, or play games in which you were very active? (Check one only.)

- None .... ☐
- 1 time .... ☐
- 2 — 3 times .... ☐
- 4 — 5 times .... ☐
- 6 or more times .... ☐

Figure 15 (cont'd)

7. Which *one* of the following describes you best for the last 7 days? Read *all five* statements before deciding on the *one* answer that describes you.

F. All or most of my free time was spent doing things that involve little physical effort..

G. I sometimes (1 — 2 times last week) did physical things in my free time (e.g. played sports, went running, swimming, bike riding, did aerobics) ....

H. I often (3 — 4 times last week) did physical things in my free time ....

I. I quite often (5 — 6 times last week) did physical things in my free time ....

J. I very often (7 or more times last week) did physical things in my free time .....

8. Mark how often you did physical activity (like playing sports, games, doing dance, or any other physical activity) for each day last week.

	Little bit	None	Medium	Often	Very Often
Monday	☐	☐	☐	☐	☐
Tuesday	☐	☐	☐	☐	☐
Wednesday	☐	☐	☐	☐	☐
Thursday	☐	☐	☐	☐	☐
Friday	☐	☐	☐	☐	☐
Saturday	☐	☐	☐	☐	☐
Sunday	☐	☐	☐	☐	☐

9. Were you sick last week, or did anything prevent you from doing your normal physical activities? (Check one.)

Yes .... ☐
No .... ☐

If yes, what prevented you? ___________________________________

APPENDIX C

IRB Approval Letters

MICHIGAN STATE
UNIVERSITY

Initial IRB Application Approval

October 18, 2013

To: Tracey Covassin
105 IM Sports Circle

Re: **IRB#** 13-990 Category: EXPEDITED 4,7
Approval Date: October 18, 2013
Expiration Date: October 17, 2014

Title: Examining the Effects and Recovery Time Following Sport-Related Concussion

The Institutional Review Board has completed their review of your project. I am pleased to advise you that **your project has been approved**.

This approval includes the study team forwarding letters of permission from the high schools before implementation via revision application(s).

The committee has found that your research project is appropriate in design, protects the rights and welfare of human subjects, and meets the requirements of MSU's Federal Wide Assurance and the Federal Guidelines (45 CFR 46 and 21 CFR Part 50). The protection of human subjects in research is a partnership between the IRB and the investigators. We look forward to working with you as we both fulfill our responsibilities.

Renewals: IRB approval is valid until the expiration date listed above. If you are continuing your project, you must submit an ***Application for Renewal*** application at least one month before expiration. If the project is completed, please submit an ***Application for Permanent Closure***.

Revisions: The IRB must review any changes in the project, prior to initiation of the change. Please submit an ***Application for Revision*** to have your changes reviewed. If changes are made at the time of renewal, please include an ***Application for Revision*** with the renewal application.

Problems: If issues should arise during the conduct of the research, such as unanticipated problems, adverse events, or any problem that may increase the risk to the human subjects, notify the IRB office promptly. Forms are available to report these issues.

Please use the IRB number listed above on any forms submitted which relate to this project, or on any correspondence with the IRB office.

Good luck in your research. If we can be of further assistance, please contact us at 517-355-2180 or via email at IRB@msu.edu. Thank you for your cooperation.

Sincerely,

Ashir Kumar, M.D.
BIRB Chair

c: Kristyn Wilhelm, Audrey Bentley, Samantha Belanger, Kristyn Wilhelm, Audrey Bentley, Samantha Belanger

Office of Regulatory Affairs
Human Research Protection Programs

Biomedical & Health Institutional Review Board (BIRB)

Community Research Institutional Review Board (CRIRB)

Social Science Behavioral/Education Institutional Review Board (SIRB)

Olds Hall
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East Lansing, MI 48824
(517) 355-2180
Fax: (517) 432-4503
Email: irb@msu.edu
www.humanresearch.msu.edu

MICHIGAN STATE
UNIVERSITY

Revision Application Approval

August 6, 2014

To: Tracey Covassin
105 IM Sports Circle

Re: **IRB# 13-990** Category: EXPEDITED 4,7
Revision Approval Date: August 5, 2014
Project Expiration Date: October 17, 2014

Title: Examining the Effects and Recovery Time Following Sport-Related Concussion (CGA134377)

The Institutional Review Board has completed their review of your project. I am pleased to advise you that **the revision has been approved**.

This approval includes adding J. Deitrick to the list of investigators and questions to the assessment tool.

The review by the committee has found that your revision is consistent with the continued protection of the rights and welfare of human subjects, and meets the requirements of MSU's Federal Wide Assurance and the Federal Guidelines (45 CFR 46 and 21 CFR Part 50). The protection of human subjects in research is a partnership between the IRB and the investigators. We look forward to working with you as we both fulfill our responsibilities.

Renewals: IRB approval is valid until the expiration date listed above. If you are continuing your project, you must submit an ***Application for Renewal*** application at least one month before expiration. If the project is completed, please submit an ***Application for Permanent Closure***.

Revisions: The IRB must review any changes in the project, prior to initiation of the change. Please submit an ***Application for Revision*** to have your changes reviewed. If changes are made at the time of renewal, please include an ***Application for Revision*** with the renewal application.

Problems: If issues should arise during the conduct of the research, such as unanticipated problems, adverse events, or any problem that may increase the risk to the human subjects, notify the IRB office promptly. Forms are available to report these issues.

Please use the IRB number listed above on any forms submitted which relate to this project, or on any correspondence with the IRB office.

Good luck in your research. If we can be of further assistance, please contact us at 517-355-2180 or via email at IRB@msu.edu. Thank you for your cooperation.

Sincerely,

H. McGee

Harry McGee, MPH
Vice Chair, Biomedical and Health Institution Review Board (BIRB)
Human Research Protection Program

c: Kristyn Wilhelm, Audrey Bentley, Samantha Belanger, Jason Avedesian, Jamie Deitrick

Office of Regulatory Affairs
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MICHIGAN STATE UNIVERSITY

Renewal Application Approval

August 25, 2014

To: Tracey Covassin
105 IM Sports Circle

Re: **IRB# 13-990** Category: EXPEDITED 4,7
Renewal Approval Date: August 13, 2014
Project Expiration Date: August 12, 2015

Title: Examining the Effects and Recovery Time Following Sport-Related Concussion (CGA134377)

The Institutional Review Board has completed their review of your project. I am pleased to advise you that the renewal has been approved.

This approval includes renewing three (3) consent forms and three (3) assent forms.

The review by the committee has found that your renewal is consistent with the continued protection of the rights and welfare of human subjects, and meets the requirements of MSU's Federal Wide Assurance and the Federal Guidelines (45 CFR 46 and 21 CFR Part 50). The protection of human subjects in research is a partnership between the IRB and the investigators. We look forward to working with you as we both fulfill our responsibilities.

Renewals: IRB approval is valid until the expiration date listed above. If you are continuing your project, you must submit an Application for Renewal application at least one month before expiration. If the project is completed, please submit an Application for Permanent Closure.

Revisions: The IRB must review any changes in the project, prior to initiation of the change. Please submit an Application for Revision to have your changes reviewed. If changes are made at the time of renewal, please include an Application for Revision with the renewal application.

Problems: If issues should arise during the conduct of the research, such as unanticipated problems, adverse events, or any problem that may increase the risk to the human subjects, notify the IRB office promptly. Forms are available to report these issues.

Please use the IRB number listed above on any forms submitted which relate to this project, or on any correspondence with the IRB office.

Good luck in your research. If we can be of further assistance, please contact us at 517-355-2180 or via email at IRB@msu.edu. Thank you for your cooperation.

Sincerely,

H. McGee

Harry McGee, MPH
Vice Chair, Biomedical and Health Institution Review Board (BIRB)
Human Research Protection Program

c: Kristyn Wilhelm, Audrey Bentley, Samantha Belanger, Jason Avedesian, Jamie Deitrick

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