10-19-2015

Test-Retest of the ImPACT in a Sample of Healthy Young Athletes

Amanda Marion O'Brien
University of Windsor

Recommended Citation

O'Brien, Amanda Marion, "Test-Retest of the ImPACT in a Sample of Healthy Young Athletes" (2015). *Electronic Theses and Dissertations*. 5466.
https://scholar.uwindsor.ca/etd/5466

Test-Retest Reliability of the ImPACT® in a Sample of Healthy Young Athletes

By

Amanda M. O’Brien

A Thesis
Submitted to the Faculty of Graduate Studies
through the Department of Psychology
in Partial Fulfillment of the Requirements for
the Degree of Master of Arts
at the University of Windsor

Windsor, Ontario, Canada

Test-Retest Reliability of the ImPACT® in a Sample of Healthy Young Athletes

by

Amanda M. O'Brien

APPROVED BY:

Dr. Nadia Azar
Department of Kinesiology

Dr. Christopher Abeare
Department of Psychology

Dr. Joseph Casey, Advisor
Department of Psychology

September 17, 2015

DECLARATION OF ORIGINALITY

I hereby certify that I am the sole author of this thesis and that no part of this thesis has been published or submitted for publication.

I certify that, to the best of my knowledge, my thesis does not infringe upon anyone's copyright nor violate any proprietary rights and that any ideas, techniques, quotations, or any other material from the work of other people included in my thesis, published or otherwise, are fully acknowledged in accordance with the standard referencing practices. Furthermore, to the extent that I have included copyrighted material that surpasses the bounds of fair dealing within the meaning of the Canada Copyright Act, I certify that I have obtained a written permission from the copyright owner(s) to include such material(s) in my thesis and have included copies of such copyright clearances to my appendix.

I declare that this is a true copy of my thesis, including any final revisions, as approved by my thesis committee and the Graduate Studies office, and that this thesis has not been submitted for a higher degree to any other University or Institution.

ABSTRACT

Baseline neurocognitive assessments are recommended to assist with concussion management in athletes, but there is no research available regarding the psychometric properties of the Immediate Post-concussion Assessment & Cognitive Testing (ImPACT), the most widely used assessment tool, in children younger than high-school age despite its assertion that it can be used as young as 11 years old. The purpose of the present study was to determine the two-week test-retest reliability of the ImPACT neurocognitive test in a healthy sample of young athletes. Participants (n=40) included healthy athletes ages 10 through 14 who were asked to complete the baseline ImPACT neurocognitive test on two occasions, two weeks apart. Overall, the ImPACT neurocognitive test has at least fair test-retest reliability with intraclass correlation coefficients for absolute agreement ranging from 0.35 to 0.74. The findings are compared to existing research, and the limitations, clinical applications and future directions for research are discussed.

DEDICATION

To my cousins, Jake & Carter, whose talent and passion for athletics has inspired me to pursue to this area of research. As they continue to grow and excel at hockey, baseball, and football, it is essential that tools and services be made available for them and other athletes in Windsor-Essex County in the event that they sustain a sports-related concussion.

ACKNOWLEDGEMENTS

The successful completion of this document would not have been possible without the support of several vital individuals. I would like to thank my supervisor, Dr. Joseph Casey, for his advice, feedback, and financial contributions in developing this project. I would also like to recognize the input and support from my thesis committee members, Dr. Christopher Abeare and Dr. Nadia Azar. Without their contributions, I would not have had access to the physical resources necessary for this project.

Thank you to my supportive cohort for the kind words of encouragement throughout this process! Without you, this entire graduate school journey would be much more difficult. Finally, thank you to my wonderful friends and family – especially my partner Dave – for always providing me with encouragement and unconditional love; I would not be where I am today without any of you!

TABLE OF CONTENTS

DECLARATION OF ORIGINALITY III

ABSTRACT IV

DEDICATION V

ACKNOWLEDGEMENTS VI

LIST OF TABLES IX

LIST OF APPENDICES X

LIST OF ABBREVIATIONS XI

CHAPTER 1 1

INTRODUCTION 1

CHAPTER 2 3

REVIEW OF LITERATURE 3

Epidemiology & Classification of Traumatic Brain Injury 3

Overview of Concussions in Sport 6

Biomechanics of Sport-related Concussions 7

Sequelae of Sport-related Concussion 9

Pediatric Sport-related Concussion 12

Management of Sport-Related Concussion 20

Evaluation of Sport-Related Concussion 24

Neurocognitive Evaluations 26

Pediatric Neurocognitive Evaluations 29

Present Study 31

CHAPTER 3 32

DESIGN AND METHODOLOGY 32

Participants 32

Measures 33

Immediate Post-concussion Assessment and Cognitive Testing (ImPACT) 33

Procedure 33

Statistical Analyses 34

CHAPTER 4 36

ANALYSIS OF RESULTS 36

Data Analysis of Assumptions 36

Normality 36

Linearity 37

Homoscedasticity / Homogeneity of Variance 37

Demographics 37

Descriptive Statistics of Outcome Variables 39

Test-retest Reliability 40

CHAPTER 5 43
CONCLUSIONS AND RECOMMENDATIONS 43
Discussion *43*
Overlap With Previous Research 44
Methodological Limitations 46
Clinical Applications 47
Future Research *48*

REFERENCES 50

APPENDICES 59
APPENDIX A – PARTICIPANT SCREENING QUESTIONNAIRE 59
APPENDIX B – IMPACT TESTING SESSION INSTRUCTIONS 61
APPENDIX C – SCATTERPLOTS OF OUTCOME VARIABLES 63

VITA AUCTORIS 66

LIST OF TABLES

Table 1. Commonly Reported Signs & Symptoms of Concussion..........................10

Table 2. Graduated Return to Play Protocol..22

Table 3. Student-Athlete Return to Play Protocol...23

Table 4. Description of ImPACT subtests...28

Table 5. One-week test-retest reliability of ImPACT in high school athletes.........31

Table 6. One-year test-retest reliability of ImPACT in high school athletes...........31

Table 7. Tests of normality...37

Table 8. Demographics...39

Table 9. Descriptive statistics..40

Table 10. Test-retest reliability coefficients between time 1 and time 2..................41

LIST OF APPENDICES

Appendix A. Participant Screening Questionnaire..59

Appendix B. ImPACT Testing Session Instructions..61

Appendix C. Scatterplots of Outcome Variables..63

LIST OF ABBREVIATIONS

ACE	Acute Concussion Evaluation
ADHD	Attention Deficit/Hyperactivity Disorder
CEI	Cognitive Efficiency Index
CNT	Computerized Neurocognitive Tests
CRT	Concussion Recognition Tool
CTE	Chronic Traumatic Encephalopathy
DAI	Diffuse Axonal Injury
DSM	Diagnostic and Statistical Manual of Mental Disorders
GCS	Glasgow Coma Scale
ICD-10	International Classification of Diseases, 10th revision
ImPACT	Immediate Post-concussion Assessment and Cognitive Testing
LOC	Loss Of Consciousness
mTBI	mild Traumatic Brain Injury
PCS	Post-Concussion Syndrome
PCSI	Post-Concussion Symptom Inventory
PTA	Post-Traumatic Amnesia
RCI	Reliable Change Index
RTL	Return-To-Learn
RTP	Return-To-Play
SIS	Second Impact Syndrome
SRC	Sport-Related Concussion
SRCC	Sport-Related Concussion Centre (University of Windsor)
SRP	Symptom Response Pattern
TBI	Traumatic Brain Injury

CHAPTER 1

INTRODUCTION

The past decade has seen a tremendous increase in the awareness of sport-related traumatic brain injury, commonly referred to as concussion. Media outlets have referred to it as a “concussion crisis” and “epidemic” based on increases in reported injuries and related lawsuits involving professional sports associations (Zuspan, 2013). Along with this escalation in media attention has been a steady increase in concussion-related publications, especially over the past 5 years (Wilde et al., 2012), and significant improvements in the development of concussion screening and assessment tools (Cantu & Hyman, 2012a; Echemendia et al., 2013), which have influenced policies and attitudes concerning sports of all levels.

Common practice for concussion evaluations is to first determine the injury characteristics, and then determine symptom status and neuropsychological dysfunction using rating scales and cognitive testing, particularly whether these symptoms are greater than pre-injury levels (Gioia, 2012). In order to complete this comparison, a baseline assessment prior to the injury should be performed. For baseline testing to increase diagnostic accuracy of concussions, the measures used must have good test-retest reliability and limited practice effects (Echemendia et al., 2013).

Research and development of the tools used in these evaluations have focused primarily on sport-related concussion in adults, followed by generalizations made to the pediatric population. For example, the most common neurocognitive tool used for this purpose is the Immediate Post-concussion Assessment and Cognitive Testing, or ImPACT for short (Lovell & Collins, 2002). This measure was developed for adults and has controversial results regarding its psychometric properties, with some studies citing good reliability (Elbin, Schatz, & Covassin, 2011) and others with the opposite results (Broglio, Ferrara, Macciocchi, Baumgartner, & Elliott, 2007). In addition, the manual claims that the tool can be used with children as young as 11 years old with norms available for children as young as age 10 (Lovell, Collins, Podell, Powell, & Maroon, 2007), but there are currently no published studies regarding the psychometric properties of the ImPACT with a population younger than age 14.

The current project seeks to contribute to the existing knowledge base through the independent validation of the ImPACT in a pediatric population. More specifically, the project investigates the two-week test-retest reliability of the measure in a healthy sample of young athletes between the ages of 10 and 14 years.

CHAPTER 2

REVIEW OF LITERATURE

Epidemiology & Classification of Traumatic Brain Injury

Traumatic brain injury (TBI) in broad terms refers to the effects following a mechanical force applied to the head, and can impact physical, cognitive, behavioural and emotional functioning (NIH Consensus Developmental Panel on Rehabilitation of Persons with Traumatic Brain Injury, 1999). TBI, even in the mildest form, is a public health concern as it is a leading cause of death and disability in North America (Greenwald et al., 2003; Pickett et al., 2004). According to the 2009-2010 Canadian Community Health Survey, almost 100,000 head injuries were reported during the previous year, of which 23,000 injuries involved youth between the ages of 12 and 19 years (Statistics Canada, 2013). High rates of TBI-related emergency room visits and hospitalizations were reported in a study that analyzed Ontario hospital records from 2002 to 2007 (Colantonio et al., 2010). In particular, there were more than 18,000 TBI episodes per population of 100,000 recorded in 2007 alone. Of these, 21% involved children under the age of 15. The high rate of TBI is also an economic concern with a total direct cost of over $151 million in 2001 as estimated by the Public Health Agency of Canada (Canadian Institute for Health Information, 2007). The main mechanisms of injury were also included in the Ontario hospital records with falls reported as the most common cause across all ages at 42%; however, 20% of the recorded head injuries were sports-related with almost 17,000 cases in those five years (Colantonio et al., 2010). In fact, it is estimated that one in every 70 visits to pediatric emergency departments across Canada is for suspected concussion, with patients aged 9 to 22 years reporting concussion symptoms most often (Ontario Neurotrauma Foundation, 2014).

TBI occurs following an external force that influences the brain in some form, and these injuries have been classified in a number of ways ranging from mild to severe. Classification systems by severity, outcome, and prognosis have all been proposed. Classification of TBI severity near the time of injury can be made using the Glasgow Coma Scale (GCS) and by identifying the interval of post-traumatic amnesia (PTA), which is the time from injury to the return of normal orientation and memory formation (Friedland & Hutchinson, 2013). The GCS assesses coma and impaired consciousness by rating eye opening, verbal response, and motor response on a 15-point scale, with a score of 13-15 considered as mild, 9-12 as moderate, and 3-8 as severe (Teasdale & Jennett, 1974). Due to the limitations associated with using a single indicator to classify TBI, the Mayo Classification for TBI Severity (Mayo System) was developed to include the following indicators: loss of consciousness; GCS score; PTA index; presence of neuroimaging abnormalities; and presence of skull fractures (Friedland, 2013). By requiring more than a single indicator of TBI severity, the Mayo System classifications are likely to be more accurate, resulting in more effective rehabilitation processes. The three main classifications for TBI in this system include a statement about the probability of injury: Definite Moderate-Severe TBI, Probable mild TBI, and Possible TBI (Friedland, 2013; Malec et al., 2007).

Various definitions and terminologies have been used to define mild traumatic brain injury (mTBI), such that there is currently no consensus regarding its definition (Yeates & Taylor, 2005). Wilde and colleagues (2012) offer a working definition of mTBI, which “occurs when there is a forceful motion of the head or neck and results in a transient alteration of mental status, such as confusion or disorientation, loss of memory for events immediately before or after injury, or brief loss of consciousness". Based on the Mayo System, a probable mTBI would be classified if a patient loses consciousness for less than 30 minutes or experiences PTA for no longer than 24 hours (Malec et al., 2007). This is compatible with the operational definition of mTBI put forth by the American Congress of Rehabilitation Medicine, which is commonly employed to diagnose mTBI (1993). The operational definition of mTBI states that:

> A patient with mild traumatic brain injury is a person who has had a traumatically induced physiological disruption of brain function, as manifested by **at least** one of the following: (1) any period of loss of consciousness; (2) any loss of memory for events immediately before or after the accident; (3) any alteration in mental state at the time of the accident (e.g., feeling dazed, disoriented, or confused); and (4) focal neurological deficit(s) that may or may not be transient; but where the severity of the injury does not exceed the following: loss of consciousness of approximately 30 minutes or less; after 30 minutes, an initial Glasgow Coma Scale of 13-15; and post-traumatic amnesia not greater than 24 hours. This definition includes: (1) the head being struck; (2) the head striking an object; and (3) the brain undergoing an acceleration/deceleration movement (i.e., whiplash) without direct external trauma to the head. It excludes stroke, anoxia, tumor, encephalitis, etc. Computed tomography, magnetic resonance imaging, electroencephalogram, or routine neurological evaluations may be normal. Due to the lack of medical emergency, or the realities of certain medical systems, some patients may not have the above factors medically documented in the acute stage. In such cases, it is appropriate to consider symptomatology that, when linked to a traumatic head injury, can suggest the existence of a mild traumatic brain injury.

Based on the Mayo System, a brain injury can also be classified as a possible TBI when the patient experiences at least one of the following symptoms: blurred vision, confusion, feeling dazed, dizziness, focal neurological symptoms, headache, or nausea (Malec et al., 2007). This is considered the least serious of all the possible TBI classifications.

Overview of Concussions in Sport

Although historically the term ‘concussion’ has been used as a synonym for mild traumatic brain injury (Wilde et al., 2012), this practice is no longer advised. Firstly, as a result of the interchangeability between these two terms, the general population assumes that a concussion *must* involve loss of consciousness (LOC) when in fact 95% of concussions do not (Cantu & Hyman, 2012b; Tator, 2012). Compared to concussions from motor vehicle or cycling accidents, LOC is least likely in sport-related concussion (SRC) due to lower-velocity impact, and instead involves disorientation or a relative impairment in consciousness (Khurana & Kaye, 2012). The term “mild” may also be particularly misleading in regards to SRC because these injuries can be quite serious, with a potential for long-term consequences especially with repetitive occurrences (Khurana & Kaye, 2012; Meehan & Bachur, 2009). Recent research has documented white matter correlates of cognitive dysfunction after mTBI up to 1 year later (Croall et al., 2014), meaning that it may not be as ‘mild’ as originally thought. Therefore, the most recent consensus statement on concussion in sport separated the definition of concussion from that of mild traumatic brain injury (McCrory et al., 2013). According to the Zurich Consensus Statement from the 4th International Conference on Concussion in Sport (McCrory et al., 2013), the term ‘concussion’ is defined as follows:

> Concussion is a brain injury and is defined as a complex pathophysiological process affecting the brain, induced by biomechanical forces. Several common features that incorporate clinical, pathologic and biomechanical injury constructs that may be utilized in defining the nature of a concussive head injury include:
>
> 1. Concussion may be caused either by a direct blow to the head, face, neck, or elsewhere on the body with an ‘impulsive’ force transmitted to the head.

> 2. Concussion typically results in the rapid onset of short-lived impairment of neurological function that resolves spontaneously. However, in some cases, symptoms and signs may evolve over a number of minutes to hours.
> 3. Concussion may result in neuropathological changes, but the acute clinical symptoms largely reflect a functional disturbance rather than a structural injury and, as such, no abnormality is seen on standard structural neuroimaging studies.
> 4. Concussion results in a graded set of clinical symptoms that may or may not involve loss of consciousness. Resolution of the clinical and cognitive symptoms typically follows a sequential course. However, it is important to note that in some cases symptoms may be prolonged. (p. 1-2)

Biomechanics of Sport-related Concussions

The biomechanics of SRC involves the sudden speeding up (acceleration) or slowing down (deceleration) of the head, followed by either a direct impact to the head or an impulse, which is a force to another part of the body that sets the head in motion without directly striking it (Mihalik, 2012). A helmet-to-helmet collision is an example of a direct impact, whereas tackling or body checking is considered an impulse due to the abrupt stopping of an opponent's body from travelling in the direction in which it was already moving (Mihalik, 2012). Although the impulse does not directly involve the head, the abrupt stopping of the body causes a whiplash effect through the neck and head resulting in movement of the brain within the skull (Cantu & Hyman, 2012c). Therefore, an athlete does not need to be struck directly in the head to suffer a concussion.

Two types of acceleration forces are involved in concussions and are represented as g-force relative to gravitational acceleration. Various studies report that concussions are likely to occur from a blow to the head that exceeds between 70 and 90 g (Hugenholtz & Richard, 1982; Ono, Kikuchi, Nakamura, Kobayashi, & Nakamura, 1980; Zhang, Yang, & King, 2004). Linear acceleration results from the application of force along a path through the brain's centre of mass, while rotational acceleration occurs when the head rotates about an axis through the brain’s centre of mass (Knudson, 2007). Following direct impact, linear force causes the brain to move backwards to collide with the back of the skull and then forwards causing a second impact with the front of the skull, typically referred to as a coup-contracoup injury. Rotational acceleration is more damaging and results from an off-center hit that causes the brain to rotate within the skull (Cantu & Hyman, 2012c). These rotational forces are thought to cause more serious injury due to neuronal shearing following rotation, as opposed to focal macroscopic brain damage caused by linear forces (Khurana & Kaye, 2012). If the rotational forces are centered specifically on the midbrain and thalamus, there is a disruption to the components of the reticular activating system leading to a loss of consciousness (Khurana & Kaye, 2012). Conversely, LOC is unlikely to occur from linear forces or whiplash effects.

Following these biomechanical forces, the brain incurs structural and metabolic changes. Structurally, there is an immediate stretching of axons and increased permeability and disruption of neuronal membranes following a concussive injury, potentially leading to diffuse axonal injury (DAI) depending on the nature of the blow (Khurana & Kaye, 2012). DAI was originally described only after a severe TBI, but there is some evidence that it also occurs following concussion (Barkhoudarian, Hovda, & Giza, 2011). The stretching of the axonal cell membranes influences metabolic processes, such as ionic flux and diffuse depolarization (Barkhoudarian et al., 2011). Following a concussive injury, there is an abrupt release of the neurotransmitter glutamate, followed by an efflux of potassium and an influx of calcium (Giza & Hovda, 2001), disrupting the neuronal membrane potential. In order to regulate this action potential, the sodium-potassium pump goes into overdrive, leading to an increase in glucose metabolism. This process quickly reduces intracellular energy stores, thus glucose is metabolized by the less efficient process of glycolysis (Barkhoudarian et al., 2011). This state of hypermetabolism leads to a cellular energy crisis, which is the likely mechanism for post-concussive vulnerability. Due to the excessive influx of calcium ions, calcium accumulates in the mitochondria, resulting in glucose oxidative dysfunction (Barkhoudarian et al., 2011). Therefore, after the initial period of glucose utilization, the concussed brain goes into a period of depressed metabolism and is less able to respond adequately to a second traumatic injury (Giza & Hovda, 2001). The vulnerability to subsequent injuries following a concussion is thought to be a result of the combination of cellular ionic disturbances, decreased cerebral blood flow, and glucose metabolic dysfunction (Barkhoudarian et al., 2011). Despite little to no evidence of post-concussive structural damage on CT or MRI scans (Shenton et al., 2012), the concussed brain experiences significant alterations in ionic balance, neurotransmitter activation, axonal integrity, and energy metabolism, and it is possible to describe the patient as being in a metabolically stressed state (Barkhoudarian et al., 2011). Therefore, the brain may be significantly distressed following a simple blow to the head, even without a display of any overt signs. In such a state, the brain is not prepared for optimal performance or to sustain another injury.

Sequelae of Sport-related Concussion

The Zurich Consensus Statement provides a list of possible clinical domains implicated following a concussion: cognitive, somatic and/or emotional symptoms, physical signs, behavioural changes, cognitive impairment, and sleep disturbance (McCrory et al., 2013). Specific signs and symptoms commonly reported following a

SRC are included in Table 1. A recent systematic review of prevalent indicators for concussion found that increased reaction time, impaired verbal learning and memory, impaired balance, and disorientation or confusion were most prevalent in early samples of concussed individuals (Carney et al., 2014). Symptomatic recovery typically occurs within two to ten days of the injury (Iverson, Brooks, Collins, & Lovell, 2006; Khurana & Kaye, 2012). This is, however, dependent on the severity of the injury and a history of previous head injuries. Concussions are heterogeneous, meaning that there is no specific symptom or cluster inherent to all SRCs making it difficult to set specific recovery parameters (McCrory, Collie, Anderson, & Davis, 2004; Patel, 2006).

Table 1
Commonly Reported Signs & Symptoms of Concussion

Mental Status	Physical/Somatic	Behavioural
Impaired level of consciousness	Headache	Personality changes
Amnesia	Dizziness/Lightheadedness	Sadness/depressed mood
Disorientation/confusion	Nausea/vomiting	Inappropriate emotionality
Forgetting game rules/plays	Ataxia/loss of balance	Low tolerance for frustration
Inability to recall score/opponent	Poor coordination	Nervousness/anxiety
Seeing stars/flashing lights	Photophobia/phonophobia	
Feeling "out of it"/"in a fog"	Slurred, incoherent speech	
Difficulty concentrating	Tinnitus	
Excessive drowsiness	Vision changes	
Slow verbal responses	Decreased playing ability	
Hallucinations	Seizure	
	Fatigue	

Note. Adapted from Meehan & Bachur (2009) & Patel (2006).

If symptoms persist for longer than one month, a diagnosis of post-concussion syndrome (PCS) can be made (Khurana & Kaye, 2012). PCS encompasses persistent symptoms and signs following a brain injury that can last for months or even years and may be exacerbated by poor acute concussion management (Patel, 2006). According to the *International Classification of Diseases, 10th Revision* (ICD-10), the presence of at least three of the following eight symptom categories must be present within one month of injury to be diagnosed with PCS: headache; dizziness; fatigue; irritability; difficulty in concentration and performing mental tasks; impairment of memory; insomnia; and reduced tolerance to stress, emotional excitement, and/or the effects of alcohol (World Health Organization, 1992). Criteria for post-concussion syndrome in the *Diagnostic and Statistical Manual of Mental Disorders, 4th edition-text revision* (DSM-IV) differs from that of the ICD-10, generating much diagnostic confusion and controversy regarding the syndrome. In fact, the diagnosis no longer exists in the new DSM-V. Based on the DSM-IV diagnostic criteria, at least 3 of the following symptoms must be present shortly after the injury and last for at least three months: easily fatigued; disordered sleep; headache; vertigo or dizziness; irritability or aggression with little or no provocation; anxiety, depression, or affective lability; changes in personality; and apathy or lack of spontaneity (American Psychiatric Association, 2000). Despite differing criteria for diagnosing PCS, it is important to understand that concussions do not resolve quickly for all athletes and that this subset of athletes is left with very real and debilitating psychological symptoms.

Despite an increase in media attention and publications involving concussion signs and symptoms in recent years, not all athletes appreciate the seriousness of sport-related concussion. More than one third do not recognize that their symptoms are a result of a concussion and many fail to report their symptoms to trained personnel (Meehan & Bachur, 2009). In a study of more than 1,500 high school football players, less than half of the athletes who sustained an SRC reported it to a trained professional because of three reasons: they either did not think the injury was serious enough to warrant medical attention, did not want to be withheld from competition, or lacked awareness of the signs and symptoms of concussions (McCrea, Hammeke, Olsen, Leo, & Guskiewicz, 2004). Other studies with collegiate and professional athletes have documented similar trends of underreporting of SRC (Delaney, Lacroix, Leclerc, & Johnston, 2000; Gerberich, Priest, Boen, Straub, & Maxwell, 1983; Kaut, DePompei, Kerr, & Congeni, 2003). Documented incidences of SRC are most likely very low in comparison to the number of actual SRCs sustained due to the common practice among athletes of not reporting their injuries. By not doing so, athletes put themselves at risk for a second injury, possibly within the same game, and significantly increase the likelihood of experiencing acute and persistent symptoms (Meehan & Bachur, 2009).

Specific risk factors for sustaining a sports-related concussion include: playing organized as opposed to leisure sports; participating in actual games rather than practice sessions; and being younger, less experienced athletes (Khurana & Kaye, 2012; Meehan & Bachur, 2009). Although the incidence is highest in contact sports, athletes in every sport risk sustaining a SRC (Powell & Barber-Foss, 1999). Female athletes may also be at a greater risk for concussion and may have poorer outcomes than their male counterparts (Dick, 2009). This finding is confounded by the fact that females tend to be more honest when reporting injuries; thus, it is unclear if there is a true gender difference in the pathophysiology of SRC or if it is simply due to reporting bias (Dick, 2009).

Pediatric Sport-related Concussion

The information presented thus far has focused primarily on sport-related concussion with adults (and late adolescents) because for a long time there was very little age-specific research on SRC. This meant that clinicians had no choice but to generalize adult concussion guidelines to pediatric populations. Over the past decade, researchers have started to focus on how concussions specifically affect children and adolescents since they manifest very differently in comparison to adults (Gioia, Isquith, Schneider, &

Vaughan, 2009; Karlin, 2011; McCrory et al., 2004). This section will summarize the relevant research regarding pediatric sport-related concussion in comparison to that of adults.

Although the incidence of SRC in athletes under the age of 15 is approximately 180 per 100,000 children per year (McCrory et al., 2004), this number is most likely much higher due to the perpetual underreporting of concussions that has become a dangerous part of some sport cultures (Institute of Medicine of the National Academies, 2013). This lack of reporting SRCs may be explained in part by the widely held belief that helmets protect the head and prevent concussion. Although helmets do reduce the risk of skull fractures, there is little to no evidence suggesting that helmets reduce the risk of or prevent concussion (Institute of Medicine of the National Academies, 2013; McCrory et al., 2004). In fact, wearing protective headgear may promote risk-taking behaviour in athletes, which actually increases the risk for sustaining a SRC (Finch, McIntosh, McCrory, & Zazryn, 2003). Lack of knowledge about the signs, symptoms, and seriousness of SRC are other reasons for underreporting.

A recent study exploring concussion under-reporting in collegiate athletes also found that they experience a great deal of pressure from coaches, teammates, parents, and fans to continue playing after a head impact (Kroshus, Garnett, Hawrilenko, Baugh, & Calzo, 2015). Athletes who experienced a SRC and felt a high level of pressure from one or more sources expressed a lower intention to report symptoms of a future suspected condition compared to peers who had experienced less pressure to return to play following a head impact (Kroshus et al., 2015). As a result, educating parents, coaches, trainers, referees, sports league officials, teachers, and health care professionals will be just as essential as educating the athletes themselves in order to improve the recognition, management, and prevention of SRC (Tator, 2012).

Many professional and collegiate organizations have now implemented concussion policies, a change that has yet to occur with most youth teams, a group particularly vulnerable to SRCs. Causes for this increase in vulnerability include a developing central nervous system, thinner cranial bones, and a larger subarachnoid space for the brain to move (Karlin, 2011). Research shows that greater neck strength and the activation of cervical muscles to brace for impact can reduce the magnitude of the head’s response to force (Eckner, Oh, Joshi, Richardson, & Ashton-Miller, 2014). Compared to adults, children have weaker cervical neck muscles and a disproportionately large head for their overall size, features that affect their ability to dissipate the energy from head impact to the rest of the body (Karlin, 2011; Meehan, Taylor, & Proctor, 2011). Education is especially important in youth leagues since the coaches are generally volunteers and it is rare to have trained staff at games, leading to reduced or delayed identification of SRC (Lovell & Fazio, 2008). In order to protect young athletes from the repercussions of SRCs, education about concussion recognition and management for all involved parties is absolutely necessary.

Children who suffer a sport-related concussion experience the same symptoms as adults (see Table 1). Similar cognitive sequelae include reduced information processing, poor attention, and impaired executive functioning, but SRC also has a significant secondary impact on a child’s educational and social attainment (McCrory et al., 2004; Ransom et al., 2015) due to longer recovery times with this population (Field, Collins, Lovell, & Maroon, 2003; McCrory et al., 2013). Adults typically return to pre-injury (or baseline) functioning within 5 to 7 days whereas the average normalization time for adolescents is 10 to 14 days (Field et al., 2003). There is a lack of data regarding the outcomes of SRC in athletes younger than 12 years of age (Purcell, 2009), but clinical experience suggests that athletes in elementary or middle school often require up to 1 month to be free of symptoms (Lovell & Fazio, 2008). Prolonged recovery in children may decrease school attendance, impacting both academic and social functioning.

The difference in recovery times between youth and adults can be explained by age-related physical and cognitive differences. In order to elicit the same level of concussive symptoms as an adult, a child must experience a biomechanical force that is 2 to 3 times greater (Ommaya, Goldsmith, & Thibault, 2002). Although somewhat counterintuitive, this finding illustrates the inverse 2/3 brain mass rule proposed by Holbourn (1943). Using three primate species with increasing brain mass, Ommaya and colleagues confirmed that larger brains were more vulnerable at lower levels of velocity and acceleration, and higher levels were required for similar injuries to the smaller brains. Therefore, a symptomatic child following a concussion will have sustained a more forceful and serious impact or impulse than an adult with the same symptoms, leading to a longer recovery. Research with immature and mature rats have identified physiological differences in responses to oxidative stress, in dopaminergic activity, in vascular response to injury, and in the susceptibility of glutamate receptors, all factors that may also play a role in the different responses to TBI in children and adult humans (Grundl et al., 1994). Finally, diffuse brain swelling following TBI appears to be more common in children and may contribute to longer recovery post-injury. Possible hypotheses for this include differences in the expression of glutamate receptors, the expression of aquaporin-4 by microglia, and in brain-water content (Bauer & Fritz, 2004). As seen with adults (Botteri, Bandera, Minelli, & Latronico, 2008), reduced cerebral blood flow was also found in children who experienced SRC (Maugans, Farley, Altaye, Leach, & Cecil, 2012). In contrast, there were no measurable neuronal, axonal, or metabolic disruptions suggesting that there are differences in neural responses to SRC between adults and children, or that the pediatric injuries were simply below the threshold for observable structural or metabolic disruption (Maugans et al., 2012).

Throughout childhood the brain is in a constant state of cognitive maturation, causing the young brain to be much more vulnerable to disruption of many essential cognitive processes (Anderson, 2001). In an earlier study, Anderson and Moore (1995) demonstrated that children who sustained a head injury under the age of 7 fared worse in neuropsychological testing later in life compared to children who were older than 7 when injured. Multiple studies have since concluded that children who sustain a head injury early on fail to develop cognitive and academic skills as quickly or as well as non-injured children (Ewing-Cobbs, Barnes, et al., 2004; Ewing-Cobbs et al., 2006; Gronwall, Wrightson, & McGinn, 1997). Ewing-Cobbs, Prasad, and colleagues (2004) found that executive functions typically acquired during preschool years, namely working memory and inhibitory control, were less developed in children who sustained a brain injury prior to age 6, supporting the rapid development hypothesis. This hypothesis suggests that skills in a rapid stage of development will be more vulnerable to disruption by TBI (Dennis, 1988). That is, skills in the process of being developed when head injury occurs are more likely to be disrupted and result in deficits, whereas over-learned or well-developed skills are less vulnerable (McKinlay, 2010).

The specific outcomes following pediatric SRC are unclear, with controversial findings regarding both short- and long-term neurobehavioural outcomes (Institute of Medicine of the National Academies, 2013), with some studies reporting evidence of deficits and others that do not (McKinlay, 2010). The controversial findings are attributed to poor and inconsistent methodology across studies, making it difficult to generalize findings of one study to another. Specific methodological problems involve the sensitivity of the measures used to assess outcome (Fletcher, Ewing-Cobbs, Francis, & Levin, 1995) and the necessity of including a control group to interpret results (McKinlay, 2010). Despite ongoing methodological problems and a lack of longitudinal studies following pediatric SRC, the following psychological domains appear to be most influenced from brain injury: attention, verbal and visual memory, behaviour, executive functions, and emotional functioning (McKinlay, 2010). A recent study examining the emotional and neuropsychological sequelae of mTBI compared to orthopedic injuries and matched controls found that those with mTBI reported higher emotional distress and PTSD-like symptoms and performed significantly worse on tests of processing speed as well as verbal learning and recall (McCauley et al., 2014). Pre-injury behaviours, family factors, and other characteristics may also predict the level of disturbance following SRC above and beyond the injury itself. Although more research is needed to identify characteristics that predict post-concussive symptoms (McKinlay, 2010; Yeates, 2010), it appears that premorbid cognitive ability may actually moderate the outcome of mTBI in children (Fay et al., 2009). That is, better cognitive functioning prior to injury suggests a more positive outcome. Parental and familial factors also play a significant role in a child's outcome following SRC (Ganesalingam et al., 2008).

Regardless of the specificity of post-concussive symptoms, the cognitive sequelae that follow SRC acutely, and possibly over the long-term, may significantly impact academic and psychosocial functioning in children and adolescents (McCrory et al., 2004). The acute symptoms of SRC have obvious effects on the child's ability to learn. Somatic symptoms, including headache, light or noise sensitivity, and fatigue, interfere with efficient information processing and concentration (Sady, Vaughan, & Gioia, 2011). Problems in attention, memory, and reaction time inhibit proper learning, especially when accompanied by emotional symptoms (i.e. anxiety), and this creates a perpetual cycle of poor learning (Sady et al., 2011). Cognitive, behavioural, and mood changes are also found to occur in children and adolescents with sleep disturbance (O'Brien, 2009), a common sequelae of mTBI. Teenagers who have sustained an mTBI demonstrate less sleep efficiency and increased wake bouts compared to controls some 3 years later (Kaufman et al., 2001). Even after controlling for injury status using orthopedic injury patients, those with a brain injury experienced more frequent sleep disturbances (Tham et al., 2012). Therefore, sleep problems in children with SRCs will also influence academic performance. Additionally, using a concussed brain to learn can worsen symptoms and prolong recovery (Majerske et al., 2008). Engaging in cognitive activity during the acute phase of a concussive head injury causes cognitive over-exertion and worsening of symptoms since the brain is under-energized due to the metabolic changes occurring after the brain injury (Sady et al., 2011). Therefore, learning and academic performance are at risk of impairment following a SRC in children and adolescents due to the associated symptoms and sleep disturbances. For these reasons, cognitive rest following SRC is the recommended, but often neglected, strategy of concussion management (McCrory et al., 2013; Valovich McLeod & Gioia, 2010).

Premorbid conditions may also prolong recovery (Gioia, Collins, & Isquith, 2008) and affect accurate symptom reporting (Gioia, Schneider, Vaughan, & Isquith, 2009). These conditions include a history of chronic headaches, migraines, attention deficit hyperactivity disorder (ADHD), learning disabilities, anxiety, and depression. Even once athletes are asymptomatic and ready to return-to-play (RTP), some continue to exhibit neurocognitive deficits (McCrea et al., 2003), highlighting both the sensitivity of cognition and the importance of cognitive evaluation following concussion.

Children with a head injury develop an increased risk of sustaining another (McCrory et al., 2004) and often experience more significant symptoms with longer recovery times following subsequent injuries (Guskiewicz et al., 2003; Karlin, 2011). If a young athlete sustains a second head injury before symptoms associated with the first have fully resolved, second impact syndrome (SIS) may occur, which is catastrophic diffuse cerebral swelling with a typically fatal outcome (Cantu, 1998). The existence of SIS in its current definition is controversial in that the only evidence for this condition is based on anecdotal case reports and the majority of these reported cases do not actually involve a second impact (McCrory, Davis, & Makdissi, 2012). Although children are more likely than adults to experience diffuse cerebral swelling following SRC (Meehan et al., 2011), most of the reported cases of SIS have also involved subdural hematoma or cerebral edema (Cantu & Gean, 2010; McCrory et al., 2012). Therefore, it may not necessarily be a second impact that causes SIS, but a single event that is serious enough to cause cerebral bleeding. Despite the controversy of SIS and its definition, sustaining another head injury before the first has resolved may still cause more serious symptoms and longer recovery periods for athletes.

Repetitive head injuries over a prolonged period of time may also lead to a neurodegenerative disease known as chronic traumatic encephalopathy (CTE) (McKee et al., 2009). CTE is associated with memory disturbances, behavioural and personality changes, Parkinsonism, and speech and gait abnormalities due to atrophy of various brain regions (McKee et al., 2009). It generally occurs years or decades following recovery from head trauma and is believed to be the result of repetitive axonal disturbances that triggers a series of metabolic, ionic, membrane, and cytoskeletal changes (Gavett, Stern, & McKee, 2011). Concrete mechanisms of this disorder remain unclear and much more research is needed. CTE is also thought to be a contributing factor to recent suicides of some professional American contact sport athletes (Omalu, Bailes, Hammers, & Fitzsimmons, 2010). Despite occurring later in life, it is essential to be aware of the risk of CTE when considering pediatric SRC since age at time of initial and subsequent head trauma may be related to its eventual expression in adulthood (Gavett et al., 2011). It is essential that youth receive appropriate concussion management in order to protect them against premature subsequent concussions and to reduce their risk of experiencing CTE as an older adult, particularly for those children who wish to continue to play their sport at competitive levels.

Management of Sport-Related Concussion

Due to the physical and cognitive effects of SRC and the risk of long-term problems following repetitive head trauma, concussion management guidelines have been developed for all ages. The most recent Zurich Consensus statement recommends physical and cognitive rest until acute symptoms have resolved, followed by a graded program of exertion prior to medical clearance and return-to-play (McCrory et al., 2013). For children, physical and cognitive rest is particularly essential but very difficult to ensure (Karlin, 2011). Physical rest means no running, playing, physical education class, or recess until they have been cleared for the light exercise stage. When recommending rest for patients, it is important to highlight that this should only occur for 1 to 2 days until the acute symptoms begin to subside. Through a randomized controlled trial, strict rest regimens have been shown not to improve outcome and may actually contribute to an increase in symptom reporting (Thomas, Apps, Hoffmann, McCrea, & Hammeke, 2015). The full graduated return to play protocol is outlined in Table 2. Only if the athlete is fully asymptomatic for 24 hours at the current level can he progress to the next one (McCrory et al., 2013). If any post-concussion symptoms occur during the graduated RTP protocol, athletes must return to the previous asymptomatic level until symptoms clear again. Same day RTP should never occur because some symptoms may have a delayed presentation (McCrory et al., 2013).

Full cognitive rest is not realistic unless asleep or comatose, so the goal is to limit cognitive activity to a tolerable level that does not exacerbate symptoms (Valovich McLeod & Gioia, 2010). For children, this means refraining from working with computers, watching television, using a cell phone, reading, playing video games, text messaging, listening to loud music, and doing homework (Karlin, 2011; Valovich McLeod & Gioia, 2010). This may be particularly difficult for children who are easily bored, but it is important to enforce these restrictions until the activities no longer exacerbate the symptoms. Attending school tends to worsen symptoms and prolong recovery, so graduated return-to-learning protocols have also been developed (Halstead et al., 2013; Lee & Perriello, 2009). The protocol is similar to the RTP guidelines in that the athlete must be asymptomatic to progress to the next level and must return to previous level if symptoms return.

Table 2
Graduated Return to Play Protocol

Rehab Stage	Objective	Functional Exercise
1. No Activity	Recovery	Symptom-limited physical & cognitive rest
2. Light Aerobic Exercise	Increase heart rate	Walking/swimming/stationary cycling; No resistance training; Keep intensity <70% max. permitted heart rate
3. Sport-specific exercise	Add movement	Sport-specific drills (e.g. skating, running); No head impact activities
4. Non-contact training drills	Exercise, coordination and cognitive load	More complex training drills (e.g. passing drills); Progressive resistance training; no contact
5. Full-contact practice	Restore confidence; Assessment of functional skills by coaching staff	Following medical clearance; participation in normal training activities, including contact drills
6. Return to play	Normal play without symptoms	Normal game play

Note. Adapted from McCrory et. al. (2013).

The Student-Athlete Return to Play Protocol (see Table 3) may be the most appropriate for use with children and youth as it combines RTP and RTL into a single entity involving initial treatment followed by five steps once symptoms are no longer present (Lee & Perriello, 2009). The important difference from typical RTP guidelines is that the *student* is taken care of first. That is, the primary goal is to get the athlete back to regular school attendance before allowing any physical activity whatsoever (Lee & Perriello, 2009).

In an attempt to legislate state-wide minimum guidelines for appropriate concussion management in schools, a bill was introduced to the U.S. Congress in January 2011 but was not enacted ("Protecting Student Athletes from Concussions Act of 2011," 2011). Some states, however, have passed such legislation. For example, Colorado passed concussion legislation for youth that requires coaches of all school sports teams and private athletic clubs to receive annual concussion recognition education ("Jake Snakenberg Youth Concussion Act," 2012). The act is named after a teenage athlete who died following SIS, a tragedy that prompted his high school and community to create a comprehensive concussion management program to protect other young athletes (McAvoy, 2013). REAP, which stands for Remove/Reduce, Educate, Adjust/Accommodate, and Pace, combines RTP and RTL strategies using a multidisciplinary team approach, which involves the family, a separate physical and academic team from the school, and a medical team to oversee recovery (McAvoy, 2013). The manual includes information and recommendations for each team member at every step of the management plan for up to 3 weeks post-concussion.

Table 3
Student-Athlete Return to Play Protocol

Rehab Stage	Objective	Functional Exercise
0. No Activity	Acute Recovery	Symptom-limited physical & cognitive rest
1. Simple Cognitive Exercise	Return to regular school attendance	Short periods of reading, focusing, and school attendance. Continue at this period, with very limited physical activity, until a full day of school is tolerated with no exacerbation in symptoms
2. Light Aerobic Exercise	Increase heart rate	Walking/swimming/stationary cycling; Low impact activity with graduate increase in intensity & duration
3. Sport-specific exercise	Add movement related to sport	Sport-specific drills (e.g. skating, running); No head impact activities
4. Non-contact training drills	Exercise, coordination and cognitive load	More complex training drills (e.g. passing drills); Progressive resistance training; no contact
5. Full-contract practice	Restore confidence; Assessment of functional skills by coaching staff	Following medical clearance; participation in normal training activities, including contact drills
6. Return to play	Normal play without symptoms	Normal game play

Note. Adapted from McCrory et. al. (2013).

There is no concussion legislation at the federal level in Canada either. A Private Member’s bill was proposed in 2011 and reintroduced in 2013 but has yet to move forward ("National Strategy for Serious Injury Reduction in Amateur Sport Act," 2013). On the other hand, the Ontario Ministry of Education released a memorandum in March 2014 that required all school boards in the province to develop and maintain a policy on concussion that involves awareness, prevention, identification, and training strategies, as well as management procedures of diagnosed concussions (Ontario Ministry of Education, 2014). In June 2014, the Ontario Neurotrauma Foundation released the first set of guidelines for diagnosing and managing pediatric concussion. This document provides separate recommendations for health care professionals, parents, and schools or community sports organizations both in advance of, during, and post-injury, along with a list of relevant tools and documents (Ontario Neurotrauma Foundation, 2014). Through the implementation of these practices at all levels of youth sport, one can better prevent, recognize, and manage concussions.

Evaluation of Sport-Related Concussion

Appropriate management of concussions ensures proper recovery, but the concussion must first be recognized and diagnosed. There are four components to a complete concussion evaluation: defining injury characteristics; identifying symptom status and neuropsychological dysfunction; establishing the reported symptoms as greater than pre-injury status; and determining any effects on the individual’s life, such as with school, work, or socially (Gioia, 2012). Evaluation of a concussion must be comprehensive and multi-faceted rather than be based on a single measure or indicator.

Immediately following a suspected concussion, a sideline assessment by a trained medical professional using the Child-SCAT3 should occur (Concussion in Sport Group, 2013a). If there is no medical professional present, the Pocket Concussion Recognition

Tool (CRT) should be used (Concussion in Sport Group, 2013b). The Child-SCAT3 is used with athletes from 5 to 12 years old and evaluates awareness and orientation using the GCS (Teasdale & Jennett, 1974) and child-Maddocks Score (Maddocks, Dicker, & Saling, 1995). The Maddocks questions inquire about the child's orientation to time and place, such as the time of day, the sport being played, and the location of the game or practice. The measure also assesses symptoms via child and parent report, and cognitive sequelae using the Standardized Assessment of Concussion-Child version (McCrea, 2001). In addition, the Child-SCAT3 includes neck, balance, and coordination examinations (Concussion in Sport Group, 2013a). This tool allows for the documentation of relevant background and injury information, and provides information to the athlete about signs to look out for and when to return to school and sport. The Pocket CRT is much less detailed and only includes signs and symptoms of suspected concussion, along with a few questions to test memory function (Concussion in Sport Group, 2013b). It also encourages athletes to seek medical assessment if any red flags are present.

The Acute Concussion Evaluation (ACE) is a tool for physicians to use to assess patients with known or suspected concussion, especially if they did not receive an initial sideline assessment. It assesses injury characteristics and post-concussion symptoms, while also evaluating risk factors for protracted recovery, red flags for emergency management, a possible diagnosis, and includes a follow-up action plan (Gioia & Collins, 2006). The measure demonstrates good internal consistency reliability and appropriate content, predictive, convergent/divergent, and construct validity (Gioia et al., 2008). Symptom rating scales, such as the Post-Concussion Symptom Inventories (PCSI), may also be used to evaluate symptom status and injury characteristics, and have been adapted for use with the pediatric population (Gioia, Isquith, et al., 2009). A full review of appropriate symptom measures and approaches for pediatric concussion is also available (Gioia, Schneider, et al., 2009).

Neurocognitive Evaluations

Whereas the aforementioned measures assess physical and somatic aspects of SRC, they provide very little information regarding the cognitive consequences. Neuropsychological domains, such as executive functions, reaction time, attention, and memory, are sensitive to head injury; thus, neurocognitive evaluations are recommended following SRC (McCrory et al., 2013). In fact, it appears that neurocognitive testing increases diagnostic accuracy compared to self-reported symptoms alone (Van Kampen, Lovell, Pardini, Collins, & Fu, 2006). Therefore, neurocognitive evaluations are now part of standard concussion evaluations.

For many years, “cognitive status [following SRC] was measured using conventional ‘paper-and-pencil’ neuropsychological tests, but these are not ideal since they were designed to detect gross cognitive impairments at a single assessment, not for mild cognitive deficits on repeated assessments” (Collie, Darby, & Maruff, 2001). Computerized cognitive tests have since been developed to address the methodological and practical concerns of conventional measures. They require less administration time and personnel, are highly accessible, have limited practice effects due to many alternate forms, can be highly randomized, and have a generally high test-retest reliability (Collie et al., 2001). Computerized tests also provide a more accurate recording of reaction time

(Kegel & Lovell, 2012), which is important to gauge performance variability on measures of psychomotor speed, memory, and information processing (Collie et al., 2001).

The most compelling part of computerized testing is that, through re-examination over brief periods of time, the athlete's performance can be tracked to gauge recovery by comparing scores to pre-injury levels, also known as return-to-baseline assessments (Kirkwood, Yeates, & Wilson, 2006). In order for this comparison to be made, the athlete should undergo a baseline assessment prior to the head injury. If a baseline assessment is unavailable for an athlete, their post-injury scores can be compared to norms that are generated with the report. Baseline testing is not currently a requirement in concussion management programs, but it is highly recommended for collision sports, particularly among children (McCrory et al., 2013; Ontario Neurotrauma Foundation, 2014). Although this protocol is thought to increase diagnostic accuracy because pre-injury confounding variables are individually controlled, the measures must have good test-retest reliability and limited practice effects to be accurate (Echemendia et al., 2013).

Many computerized neurocognitive tests (CNTs) have been developed for adults (Meehan, d'Hemecourt, Collins, Taylor, & Comstock, 2012), but the most widely used one is the Immediate Post-concussion Assessment and Cognitive Testing, or ImPACT for short (Lovell et al., 2007). In fact, this test is used by trainers in Major League Baseball, the National Hockey League, the National Football League, and World Wrestling Entertainment (ImPACT Applications, 2014). The ImPACT yields composite scores for Verbal and Visual Memory, Reaction Time, Visual Motor Speed, and Impulse Control from six subtests, scores that represent deficits in attention, memory, and cognitive speed if lower than those at baseline (Lovell et al., 2007). The description of each subtest is available in Table 4. A *Cognitive Efficiency Index,* which is an index of the trade off between speed and accuracy, is calculated from the Symbol Match test (ImPACT Applications, 2011). Speed is measured by the number of items correctly clicked whereas accuracy is the number of items correctly identified on the memory component at the end of the subtest. The typical range of scores is from 0 to approximately .70 with a mean of .34. A higher score indicates that the athlete did well on both speed and memory with lower scores indicating poor performance on speed and memory. A *Reliable Change Index (RCI)* is also provided for post-injury assessments and these scores represent the magnitude of changes from the baseline test, or from age- and gender-stratified normative scores if no baseline is available (Lovell et al., 2007).

Table 4
Decription of ImPACT subtests

Subtest	Cognitive Domain	Description of Task
[a]Word Memory	Attention; Verbal recognition memory	12 target words presented, then tested for recall via presentation of a 24-word list by choosing yes or no if previously displayed
[a]Design Memory	Attention; Visual recognition memory	12 target designs presented, then tested for recall via presentation of 24 designs by choosing yes or no if previously displayed
X's & O's	Visual working memory; visual processing/visual motor speed	Random assortment of X's and O's presented for 1.5sec and 3 items are highlighted in yellow and subject is to remember location. Includes distractor reaction time task between administrations to interfere with memory rehearsal. After distractor, subject asked to click where the yellow objects were previously shown.
Distractor (X's & O's)	Choice reaction time; Visual motor processing speed	Subject asked to press Q if red circle appears and P if blue circle appears as quickly as possible.
Symbol Match	Visual processing speed; Visual learning & memory	Common symbols are presented and under each is a corresponding number (1 to 9). Subject must click matching number as quickly as possible and remember these pairings. After 27 trials, symbols disappear from grid and subject is asked to recall the correct pairing by clicking the appropriate number button
Colour Match	Choice reaction time; Impulse control & response inhibition	Word is displayed in the same colour as the word or in a different colour and subject must click as quickly as possible only if the word is presented in matching ink.
Three Letters	Working memory; Visual-motor response speed	5 separate trials; Presented with three consonant letters on screen, then a distractor task appears (required to select numbers in backwards order from 25 as quickly as possible). After 18sec, distractor task disappears and subject asked to recall the three letters.

Note. From ImPACT Applications (2011).
[a] Delayed recall tests after all other subtests have been completed.

The technical manual for the online version of the test contains psychometric properties and reports good overall reliability, sensitivity, and specificity for injured vs. non-injured athletes, as well as good validity with others tests from similar domains (ImPACT Applications, 2011). Independent studies of ImPACT's psychometric properties with adult populations have had mixed results. Studies of the test-retest reliability coefficients for each composite score during shorter time periods report a range between .23 and .88 (Broglio et al., 2007; Schatz & Maerlender, 2013); a similar range in reliability coefficients were found for 1 to 3 year test intervals (Elbin et al., 2011; Schatz, 2009). Conversely, test-retest reliability at one-month, one-year, and two- year intervals were high, ranging from .76 to .81 for memory and .76 and .88 for speed (Schatz & Maerlender, 2013).

Multiple validity studies have demonstrated weak to moderate, but statistically significant correlations with one or more neuropsychological tests, as well as sensitivity and specificity of at least 80% (Resch, McCrea, & Cullum, 2013). The clinical application of ImPACT in return-to-play protocols is questioned due to its psychometric inconsistencies and it is recommended that ImPACT scores not be the sole factor in determining RTP status (Mayers & Redick, 2012). Instead, the test should be used in conjunction with other tools to measure recovery.

Pediatric Neurocognitive Evaluations

Given the serious implications of pediatric sport-related concussions, this population should receive similar, yet separate evaluations from those of adult athletes. Due to the cognitive maturation occurring at this age, adult tools are not necessarily appropriate for use with children and developmentally sensitive tools are required. In response to this need, a model of pediatric concussion assessment has been proposed that encompasses multiple domains of evaluation. Specifically, the recommended measures of the Pediatric Concussion Battery (Gioia, Isquith, et al., 2009) comprise a computerized neurocognitive test (CNT), the ACE, the PCSI, the Multidimensional Fatigue Scale of the Pediatric Quality of Life Scale, Version 4.0 (Varni, Burwinkle, & Szer, 2004), the Behaviour Rating Inventory of Executive Function (Gioia, Isquith, Guy, & Kenworthy, 2000), and a measure of the child's mood. The issue with this proposed battery is that there are currently no published pediatric CNTs. The traditional ImPACT can be administered to athletes age 11 to 60, but there is currently nothing available for younger children. Although a pediatric adaptation of the ImPACT is currently in development for children aged 5 to 12 years, it has not yet been released. Therefore, clinicians, parents, and coaches do not have any appropriate tools to measure baseline and post-injury neurocognitive functioning in children and youth.

The ImPACT manual states that the measure is appropriate for children as young as 11 years old (Lovell et al., 2007). Even though clinicians are currently using this tool for baseline and post-injury assessments in youth athletes, there is little to no research available specific to the younger age group. The technical manual (ImPACT Applications, 2011) provides combined gender norms for various age groups starting as young as 10 years old, but all of the reliability and validity studies, from both the ImPACT team and independent investigators, were completed with high school or collegiate athletes. There are currently no published studies examining the psychometric properties of the ImPACT in athletes younger than 14 years old, and the reliability of the measure for children is assumed from research with high school athletes. Overall, the

ImPACT appears to demonstrate adequate short- and long-term test-retest reliability with high school athletes (see Tables 5 and 6).

Table 5

One-week test-retest reliability of ImPACT in high school athletes

Composite	Time 1 ^{a}	Time 2 ^{a}	t^{b}	*p*
Verbal Memory	88.68 (9.5)	88.84 (8.09)	-0.17	0.86
Visual Memory	78.70 (13.39)	77.48 (12.67)	0.85	0.40
Reaction Time	0.543 (0.087)	0.536 (0.063)	0.97	0.34
Processing Speed	40.54 (7.64)	42.24 (7.06)	-3.26	0.002

Note. Adapted from Iverson, Lovell, and Collins (2003).

[a] mean (standard deviation)

[b] df=55, *t* = paired sample t-test

Table 6

One-year test-retest reliability of ImPACT in high school athletes

Composite	Time 1^{a}	Time 2^{a}	*r*	ICC
Verbal Memory	85.6 (9.1)	86.4 (9.1)	.45	.619
Visual Memory	72.0 (12.7)	75.5 (14.0)	.55	.703
Motor Speed	37.5 (6.7)	39.8 (6.8)	.74	.851
Reaction Time	0.59 (0.08)	0.56(0.07)	.62	.761
Symptom Scale	4.7 (8.5)	4.4 (8.1)	.40	.569

Note. Adapted from Elbin et al. (2011).

[a] mean (standard deviation)

Present Study

The purpose of the present study was to provide independent validation of the ImPACT in a healthy sample of youth athletes in two phases. Phase one of the study was to determine the test-retest reliability of the baseline assessment of the ImPACT neurocognitive task at a two- to three-week interval. A baseline neurocognitive assessment was administered to athletes 11 through 14 years of age, followed by a retest two weeks later. Based on previous research with adolescents and adults, the ImPACT should demonstrate good test-retest reliability. The second phase of the study, which is currently ongoing, is to assess the construct validity of the measure by comparing the neurocognitive performance on the ImPACT to scores on paper-and-pencil measures of learning, memory, and processing speed. A side goal of the study was to provide education to parents and athletes through the dissemination of concussion resources.

CHAPTER 3

DESIGN AND METHODOLOGY

Participants

Power analysis ($\alpha = .05$, $[1 - \beta] = .80$) indicated that using the proposed methodological design and statistical analysis, 67 total participants would be needed to detect a statistically significant difference of a medium effect size. Young athletes from the Windsor-Essex community were recruited for the study through contact with coaches of local sports teams and word-of-mouth of parents and athletes in the community. Interested parents then contacted the primary investigator to determine whether their child was eligible to participate. Parents were asked to complete an online research participant questionnaire (see Appendix A) using a secure survey link in order to acquire relevant background information about the child, such as previous head injuries, medical problems, and/or diagnoses of a learning disability or ADHD. In lieu of monetary compensation, the incentive for participants was a free baseline test and access to free neuropsychological consultation in the event that the youth sustains a concussion over the course of the next year. At this point, they would be subject to and benefit from neuropsychological concussion management through the SRCC for up to one year through the return-to-play protocol that is recommended by the Ontario Neurotrauma Foundation (2014).

If the athlete was eligible for the study, the participants were scheduled for two baseline sessions to assess the test-re-test reliability of the measure. Participants were excluded if they had sustained a concussion within the last three months or were still recovering from a past concussion. The University of Windsor Research Ethics Board approved the protocol for the study, and both participants and their parents provided informed consent for their participation. Forty-three athletes between the ages of 10 and 14 years old participated in the study, but three subjects were lost to follow-up resulting in a final sample of 40 subjects.

Measures

Immediate Post-concussion Assessment and Cognitive Testing (ImPACT)

The computerized baseline neurocognitive test used for this study was the Immediate Post-concussion Assessment and Cognitive Testing (ImPACT; (Lovell & Collins, 2002). The subtests were administered in the same order as listed in Table 4, except for the delayed memory trials, which were given at the end of the test. The ImPACT was administered to participants at the University of Windsor in a computer lab in the Human Kinetics building. Participants were seated comfortably at a desktop computer, and a wired mouse and keyboard was used to respond. The computer did not have any additional applications running during the assessment so as to not influence the timing accuracy of the program. For group administrations, the children were seated at every other computer to minimize potential distractions. Before administering the test, the examiner introduced the purpose of the activities, described the importance of reporting concussions, and provided specific instructions that are included in Appendix B. The children were able to read the on-screen instructions for each subtest, but the examiner was also available to answer any questions as needed.

Procedure

Participants were asked to come to the University of Windsor to complete the computerized neurocognitive baseline test (ImPACT) in groups of up to 12 athletes. The measure was administered as per the instructions in the manual. Participants first responded to the symptom checklist, which asks whether they are experiencing any of the common concussion symptoms at the time of testing. Next, the participants progressed through the six neurocognitive activities for 30 to 45 minutes. The athletes then returned approximately two weeks later to complete the baseline assessment again to assess the test-retest reliability of the measure. The same instructions were provided and participants completed the baseline test, including the symptom checklist and the neurocognitive activities for a second time.

After the first session, parents were emailed a copy of the Brain Injury Guide for Youth (Kutcher, 2015) and a link for a 5-minute video clip that targets children and introduces the importance of reporting concussions (Evans, 2011). Parents were encouraged to watch this video with their children, which acted as an education component for the athletes. A concussion recognition mobile application called Concussion Recognition and Response (Gioia & Mihalik, 2012) was also recommended as a useful tool for parents and coaches.

Statistical Analyses

Prior to performing any analyses, the data was coded in order to remove all identifying information. The identifying data remained in an encrypted file for access if an athlete returns for a post-injury evaluation. The consent forms were also kept separate from the data. All data analyses were performed used IBM SPSS Statistics, Version 22.0. Unless otherwise noted, an alpha level of .05 was used to determine statistical significance.

Correlational analyses were used to determine whether the athletes' test scores were stable at different testing times. The literature suggests some controversy over which analysis is best for determining test-retest reliability of measures, with some advising the use of Pearson product-moment correlations (Rousson, Gasser, & Seifert, 2002) and others claiming that intra-class correlations are most appropriate for test-retest situations (Baumgartner, 2000; Weir, 2005). A common criticism of the use of Pearson product-moment correlation for test-retest reliability is that it is not sensitive enough to detect systematic error, with empirical support for this limitation dating back to the 1970s (Baumgartner & Jackson, 1975). Despite this, Rousson et al. (2002) argued that product-moment correlations are more appropriate than intra-class correlations in test-retest situations since systematic error is assumed to be due to learning effects and need not be taken into account when assessing reliability. As such, both Pearson product-moment and intra-class correlations were used to analyze the test-retest reliability of the ImPACT in this study. The standard error of measure (*SEM*) was also calculated to quantify the accuracy of the scores across testing times.

The magnitude of the statistical effects were described according to guidelines from Cohen (1988). For Pearson's correlation (r), a coefficient of 0.5 represents a large effect, 0.3 a medium effect and 0.1 a small effect. The coefficient of determination (r^2) was also calculated for Pearson's correlation coefficients to demonstrate the amount of shared variance between the scores at time 1 and time 2. Eta-squared (η^2) was calculated as an estimate of effect size for the intra-class correlations.

CHAPTER 4
ANALYSIS OF RESULTS

Data Analysis of Assumptions

Prior to hypothesis testing, the data was analyzed to determine adherence to the assumptions of Pearson's product-moment and intra-class correlations. Tested assumptions include univariate normality, linearity, and homogeneity of variance. Assumptions were verified on each of the following variables at both Time 1 and Time 2: Verbal Memory, Visual Memory, Reaction Time, Visual-Motor Speed, and the Cognitive Efficiency Index (CEI).

Normality

The assumption of normality was verified by analyzing skewness, kurtosis, and Shapiro-Wilk statistics. The z-scores for skewness and kurtosis were within the conventional cut-offs of significance (i.e. skewness less than |2| and kurtosis less than |3) for most composite scores, except Reaction Time and the CEI at Time 2. The Shapiro-Wilk tests of normality were nonsignificant for many variables, except for both of the Verbal Memory scores, Visual-Motor Speed at Time 1, and Reaction Time and the CEI at Time 2. See Table 7 for a summary of the normality test statistics. The values for Reaction Time and CEI at Time 2 were outside their respective cut-offs on all three tests of normality, violating the assumption for these two variables. The assumption of normality was met for the remaining eight variables. No corrections were made regarding the violations because only two variables were affected and normally distributed data is not essential to the conclusions of the analyses.

Linearity

The assumption of linearity was verified by analyzing the scatterplots of the paired variables (i.e. plots of Time 1 and 2 for each composite variable). Based on visual inspection, the five pairs of variables did not demonstrate a curvilinear relationship; therefore, the assumption of linearity was met. The linear scatterplots are included in Appendix C. A few outliers are visible in these scatterplots, particularly for the CEI; however, they were not removed due to the small sample size.

Table 7

Tests of Normality

Composite	Skewness	Kurtosis	Shapiro-Wilks
Verbal Memory Time 1	-.783	.060	**.020**
Verbal Memory Time 2	-.863	-.265	**.002**
Visual Memory Time 1	-.691	.112	.092
Visual Memory Time 2	-.092	-1.089	.109
Visual-Motor Speed Time 1	.871	1.081	**.040**
Visual-Motor Speed Time 2	-.029	.497	.842
Reaction Time 1	.578	.054	.243
Reaction Time 2	**2.324**	**7.68**	**.000**
Cognitive Efficiency Index 1	-.056	-.518	.792
Cognitive Efficiency Index 2	**-3.148**	**15.235**	**.000**

Note. Boldface indicates significance and violation of assumption

Homoscedasticity / Homogeneity of Variance

The assumption that the variances are roughly equal must be verified as well because the calculations of the intra-class correlation include the F-test. Therefore, scatterplots of the error terms were visually inspected for homoscedasticity, a measure of homogeneity of variance. Each scatterplot displayed homoscedasticity; therefore, this assumption was also met.

Demographics

Data pertaining to participant demographics, including history of concussion and other neurodevelopmental disorders, were collected for the purposes of sample description. Demographic variables include participant’s age, gender, ethnicity, sport played, parental level of education, history of concussion/head injury, and presence of ADHD or learning disabilities.

The final sample consisted of 40 participants, with females representing only 15% of the subjects. The ages of the participants ranged from 10 to 14 years old. See Table 8 for detailed demographic information. All participants spoke English as their primary language. The majority of the sample, 55%, self-identified as being of Caucasian ethnicity and the majority of parents had earned at least a college diploma (87%). All of the athletes played at least one sport, with 60% of participants playing two or more sports. Hockey was the most common sport reported among participants at almost 78%, along with soccer (38%), baseball (18%), lacrosse (15%), and football (13%). Only one of the children had a diagnosis of ADHD and two subjects have been identified as having a learning disability.

Approximately 35% of participants (n=14) have previously experienced a head injury and/or concussion according to parental reports, with one additional parent indicating that they were unsure if their child had ever experienced a head jury. Of these athletes with previous head injuries, 86% were male and the majority had been sustained while playing hockey (57%). Other causes of injury included playing lacrosse, soccer or football, and falling while playing at school or on the playground. Of these injuries, 21% resulted in a loss of consciousness of approximately 10 seconds and 21% (n=3) have had more than one head injury. In the questionnaire, parents were asked whether their child had ever experienced a head injury and a concussion as two separate questions. Whereas many parents answered consistently, 43% did not, demonstrating that there is a potential misunderstanding regarding a difference between these two terms. After endorsing their child's previous head injury, three parents answered no to the question about concussion, two answered that they were unsure, and another left the concussion section blank.

Table 8
Demographics

	n	%
Gender		
Male	34	85
Female	6	15
Age		
10	1	2
11	8	20
12	15	38
13	10	25
14	6	15
Language		
English	40	100
Ethnicity		
First Nations	6	15
Asian descent	1	2.5
Hispanic/Latina	1	2.5
White/Caucasian	22	55
Other/Blank	10	25
Parental Education		
High school graduate	3	7
Some college	2	5
College graduate	17	43
Some university	2	5
University graduate	5	12
Graduate degree	11	28
Previous Head Injuries		
No	25	63
Yes	14	35
Not sure	1	2
Sport		
Hockey		78
Soccer		38
Baseball		18
Lacrosse		15
Football		13

Descriptive Statistics of Outcome Variables

The composite scores for the ImPACT were used as outcome variables for the test-retest reliability analyses, namely Verbal Memory, Visual Memory, Reaction Time, Visual-Motor Speed, and the Cognitive Efficiency Index at both time 1 and time 2. The average time interval between tests was 14.43 days with a standard deviation of 1.52 and range of 12 to 20 days. The mean, standard deviation, and 95% confidence interval for the outcome variables are summarized in Table 9. A dependent-sample t-test was performed to determine whether there were significant differences between the mean scores at time 1 and time 2. Scores on Verbal Memory, Visual Memory, and Visual-Motor Speed were significantly higher at time 2 compared to the first test. Based on the analysis, Reaction Time and the Cognitive Efficiency Index were the only composites that did not demonstrate significant practice effects.

Table 9
Descriptive Statistics

	Time 1		Time 2			
Composite	*M (SD)*	95%CI	*M (SD)*	95%CI	*t*	*p*
Verbal Memory	83.05 (11.17)	79.48 – 86.62	87.50 (9.61)	84.43 – 90.57	-3.25	0.002
Visual Memory	71.33 (12.60)	67.29 – 75.36	76.90 (13.28)	72.65 – 81.15	-2.77	0.009
Reaction Time	0.668 (0.08)	0.616 – 0.703	0.667 (0.104)	0.633 – 0.70	0.10	0.921
Visual-Motor Speed	30.94 (6)	29.02 – 32.86	32.83 (7.84)	30.32 – 35.33	-2.47	0.018
Cognitive Efficiency Index	0.297 (0.14)	0.252 – 0.342	0.310 (0.214)	0.242 – 0.378	-0.40	0.693

Test-retest Reliability

In order to determine the test-retest reliability of the neurocognitive component of the ImPACT, Pearson product-moment and intra-class correlations (ICC) were calculated using the five main composite scores as outcome variables. Pearson's correlation (denoted as r) was used to determine the strength and significance of the relationships between the paired outcome variables at time 1 and time 2. The correlations for all outcome variables were highly significant with a medium effect of at least 0.3 (see Table 10). The coefficient of determination (r^2) was calculated to determine the amount of shared variance in the relationship, and Visual-Motor Speed had the most shared variance across testing times with 62%, followed by Verbal Memory at 44%. Visual Memory, Reaction Time, and the CEI had much less shared variance at 27%, 24%, and 14%, respectively.

Based on recommendations from the review by Weir (2005), a two-way random-effects model of intra-class correlation (ICC 2,1) using an absolute agreement definition was performed and the results are summarized in Table 10. Absolute agreement looks at the reliability of individual scores rather than the general consistency among all responses, and it is a general indicator of test-retest reliability. Based on the results, the ImPACT test scores appear to have at least fair agreement among participants at a two-week interval with ICCs ranging from 0.35 to 0.74. The Visual-Motor Speed Composite scores were the most stable with strong agreement, while Verbal Memory scores had a moderate level of agreement. Only fair agreement between scores was shown for the remaining Composites: Visual Memory, Reaction Time and the CEI.

Table 10

Test-retest Reliability Coefficients between Time 1 and Time 2

	Pearson			ICC		
Composite	*r*	*p*	r^2	*R*	η^2	*SEM*
Verbal Memory	0.662	0.0001	0.44	0.604	0.79	6.12
Visual Memory	0.516	0.001	0.27	0.477	0.72	9.01
Reaction Time	0.488	0.001	0.24	0.477	0.74	0.07
Visual-Motor Speed	0.787	0.0001	0.62	0.738	0.86	3.42
Cognitive Efficiency Index	0.377	0.017	0.14	0.350	0.67	0.14

Note. For ICC, 0.3-0.4 *fair* agreement; 0.5-0.6 *moderate* agreement; 0.7-0.8 *strong* agreement

The effect size of the ICCs were determined using eta-squared, which describes the amount of variance at time 2 as explained by time 1. Again, Visual-Motor Speed and Verbal Memory demonstrated the largest effect, with the amount of variance in the scores at time 2 explained by time 1 at 86% and 79%, respectively. The amount of explained variance for Reaction Time, Visual Memory, and the CEI were 74%, 72%, and 67%, respectively, values that are much higher compared to the amount of shared variance found using r^2.

Weir (2005) also suggests the standard error of measurement (*SEM*) as an important statistic to report in test-retest reliability studies because it represents an absolute index that “quantifies the precision of individual scores on a test”. The *SEM* for the difference score of each outcome pair was calculated from the square root of the mean squares of the error (residual) term for each variable, as recommend by Weir (2005), and are also listed in Table 10. Reaction Time and the CEI appear to have the most accurate measurements across time with very low *SEM*s, while the two Memory Composites are much less accurate with high *SEM*s. It is important to keep in mind that the scores for Reaction Time and the CEI are expressed as decimals, so their range of variability is much more restricted than for scores expressed as whole numbers, potentially skewing the comparison of *SEM*s between the composite scores.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Discussion

The present study sought to gauge the appropriateness of using the ImPACT with children by determining the test-retest reliability of the measure at a short time interval. Specifically, the scores of each Composite were analyzed for agreement when administered approximately two weeks apart to ensure that the baseline scores of healthy athletes are stable across time. Without stable baseline measurements, clinicians cannot reliably use negative variations of post-injury evaluations from baseline to make concussion diagnoses and/or return-to-play decisions.

The suggested standards for reliability coefficients of clinical measures are at least 0.70 to be considered acceptable, and a value of 0.50 or less signifies poor reliability (Barker, Pistrang, & Elliott, 2015). Therefore, the results of this study suggest that the composite scores of the ImPACT are somewhat reliable for children across time. The Visual-Motor Speed Composite score had the highest agreement between testing sessions and was the only score to demonstrate good reliability (i.e. coefficient above 0.70). Although Reaction Time and the Cognitive Efficiency Index had fair agreement and were the most accurate, the scores illustrate poor reliability. There was much more variability among the accuracy of the scores on the memory composites. In addition, Verbal and Visual Memory demonstrate marginal and poor reliability, respectively, according to the suggested standards mentioned above. Therefore, the ImPACT neurocognitive test demonstrates marginal reliability when used with children; consequently, it should not be the sole factor in determining concussion diagnoses and return-to-play readiness. A measure with strong agreement between scores would be much more desirable and clinically useful.

Overlap With Previous Research

Although the findings from this study are in line with previous research from adolescent and adult population, direct comparisons to other studies proved difficult due to differences in statistical analyses and test-retest intervals. Some studies have evaluated the reliability after a short interval of one week (Iverson et al., 2003), while others evaluate the reliability after one month (Broglio et al., 2007; Schatz & Ferris, 2013), one year (Elbin et al., 2011), or even longer (Schatz, 2010).

Iverson et al. (2003) used Pearson correlation coefficients and dependent-samples t-tests to investigate the one-week test-retest reliability of 56 non-concussed athletes with an average age of 17 years. Their test-retest correlation coefficients ranged from 0.67 to 0.85, which are similar to those of the present study. Iverson and colleagues then used a dependent-samples t-test to test for within person differences across testing sessions. They found that the Processing Speed scores (now referred to as the Visual-Motor Speed Composite on the current version of the ImPACT) were significantly different (p=0.002), which the authors attributed to practice effects. Practice effects for Visual-Motor Speed were also found in the present study, with Verbal & Visual Memory also demonstrating the effect.

Another test-retest reliability study with 369 high school athletes looked at stability of scores after a one-year time interval using intraclass correlations (Elbin et al., 2011). These results were in line with the present study in that motor-processing speed was the most stable (0.85); however, the Verbal and Visual Memory Composites were more stable after one year (0.70 and 0.62, respectively) compared to the results of the present study. Therefore, Elbin et al. (2011) found that the ImPACT is a stable measure of cognitive performance at a one-year time interval for high school aged athletes. Practice effects were unlikely to have been a factor at the one-year retest interval, leading to more stable measurements across time.

There has been much more psychometric research on the ImPACT using collegiate or adult athletes, with mixed results at both short and long time intervals as reviewed by Mayers and Redick (2012). Schatz and Ferris (2013) investigated the one-month test-retest reliability with 25 undergraduate students and found similar results as the present study. Specifically, they obtained ICCs of 0.88 for Visual-Motor Speed, 0.79 for Verbal Memory, 0.77 for Reaction Time, and 0.60 for Visual Memory. Broglio et al. (2007) had very different results when testing the reliability after 45 days with 73 undergraduate students (mean age of 21 years), with ICCs ranging from 0.23 on Verbal Memory to 0.39 on Reaction Time, reliability values that are not generally considered acceptable for measures with a clinical purpose.

Therefore, the results from the present study are similar to those in previously published studies of test-retest reliability using samples of different ages and different retest intervals. Despite the variability among previous research, motor-processing speed appears to be the most stable measurement regardless of age or interval length, with much more variability among the memory composites. Overall the ImPACT appears to be only marginally reliable for use with children.

Methodological Limitations

The present study is not without methodological limitations, which may have affected the results, and in turn the conclusions of the study. The primary limitation is the small sample size, which can influence the statistical power of the results. Post-hoc power analyses using G*Power software (Buchner, Erdfelder, Faul, & Lang, 2009) were performed for the bivariate correlations for each outcome pair. Although the CEI had very low power ($1 - \beta = 0.685$), the other four variables had high power ranging from 0.90 to 0.99. In addition, data can be unstable with small sample sizes, yielding high variance. This may explain the large standard errors of measurement for many of the composite scores.

Another limitation is that two variables did not meet the assumption of normality, which may influence the precision of the statistical results. This is because outliers have more influence over the distribution with smaller samples. With a larger sample, the outliers could have been removed or may not have had as large of an effect on the normal distribution of the variables. The outliers were not removed from the present study for two reasons. Firstly, removal of the outliers would reduce an already small sample size. Secondly, since the baseline assessments were valid, the data from these individuals would be used clinically for comparison if a post-baseline injury occurred. In this way, the analyses represent a ‘real-world’ estimate of reliability.

In addition to the size, the gender distribution of the sample is skewed with only 14% female representation. This may affect the ecological validity of the measure in that the results of the study may be more generalizable to males between the age of 10 and 14 rather than females. Moreover, gender differences in test-retest reliability could not be investigated with this particular sample. Although the sample was also heterogeneous in terms of previous concussion history, with a large portion of participants having experienced at least one head injury in the past, this is representative of clinical populations who are using the ImPACT.

A final limitation to the study is the short retest interval of two weeks, which may not have clinical applicability since baseline assessments in children are assumed to be stable for the length of a season up to a maximum of one year. Although this is true, scores should be stable in the short-term and over longer periods if the measure is truly reliable, especially since multiple post-injury evaluations often happen over fairly short time intervals (i.e., every few days or within a few weeks) to track recovery. This notion is especially important in the present study since this is the first study to establish the reliability of the ImPACT in a younger sample.

Clinical Applications

Despite the limitations discussed, the results from the present study have direct clinical applications as many medical professionals use the ImPACT for making concussion diagnoses and return-to-play decisions. The neurocognitive scores were fairly stable at a two-week test interval with this sample, which means that the ImPACT may be used with athletes below the age of 14; however, clinicians should be cautious when making interpretations based on changes from baseline alone due to only marginal reliability. Diagnoses or return-to-play decisions should not depend solely on the Reliable Change Indices of the ImPACT scores, but should instead encompass a larger evaluation complete with ratings of post-concussion symptoms, mood and behaviour inventories, balance testing, and clinical interviews as suggested by Gioia, Isquith, et al. (2009).

Future Research

The results and methodology used in this study suggest multiple lines of research that should be explored in the future. First, recruitment for the present study should continue in order to acquire a larger sample size to increase statistical power and the strength of the results. Stronger conclusions can often be made when the sample is large and a good representation of the true population. Recruitment should specifically target female athletes in order to achieve an even gender distribution.

In addition, the test-retest reliability of the ImPACT should also be explored with this age group at longer test intervals, for example after six months or one year. A caveat to this line of research is that the athlete's baselines scores may increase naturally after one year due to cognitive maturation occurring during the pre-adolescent years; therefore, the reliability coefficients may not be as stable at one year compared to shorter intervals.

Although the results of the present study somewhat support the use of the ImPACT with children between 10 and 14 years old, there is much room for improvement. The measure does not have good reliability and was designed for use with adults. It is imperative that a developmentally appropriate neurocognitive baseline measure is developed that can be used exclusively with children and young adolescents. Furthermore, the convergent and divergent validity of the measure has yet to be determined with a younger age group. That is, do the Composite scores measure what they claim to be measuring? Is there a difference in construct validity with the younger age group? To answer these questions, a validity study is needed, which would provide more evidence for the appropriateness of using the ImPACT in children. Whether or not poor validity of the ImPACT is discovered, the development of a pediatric measure is essential to ensure proper concussion management among our youth.

REFERENCES

American Psychiatric Association. (2000). *Diagnostic and statistical manual of mental disorders (4th ed., text rev.)*. Washington, DC: Author.

Anderson, V. (2001). Outcome from mild head injury in young children: a prospective study. *J Clin Exp Neuropsychol, 23*(6), 705-717.

Anderson, V., & Moore, C. (1995). Age in injury as a predictor of outcome following pediatric head injury: A longitudinal perspective. *Child Neuropsychology, 1*(187-202).

Barker, C., Pistrang, N., & Elliott, R. (2015). *Research Methods in Clinical Psychology: An Introduction for Students and Practitioners*: Wiley.

Barkhoudarian, G., Hovda, D. A., & Giza, C. C. (2011). The molecular pathophysiology of concussive brain injury. *Clinical Journal of Sports Medicine, 30*, 33-48. doi: 10.1016/j.csm.2010.09.001

Bauer, R., & Fritz, H. (2004). Pathophysiology of traumatic injury in the developing brain: an introduction and short update. *Experimental and Toxicologic Pathology, 56*(1), 65-73.

Baumgartner, T. A. (2000). Estimating the Stability of Reliability of a Score. *Measurement in Physical Education and Exercise Science, 4*(3), 175-178.

Baumgartner, T. A., & Jackson, A. S. (1975). *Measurement for evaluation in physical education*. Boston: Houghton Mifflin.

Botteri, M., Bandera, E., Minelli, C., & Latronico, N. (2008). Cerebral blood flow thresholds for cerebral ischemia in traumatic brain injury: A systematic review. *Critical Care Medicine, 36*(11), 3089-3092.

Broglio, S. P., Ferrara, M. S., Macciocchi, S. N., Baumgartner, T. A., & Elliott, R. (2007). Test-Retest Reliability of Computerized Concussion Assessment Programs. *Journal of Athletic Training, 42*(4), 509-514.

Buchner, A., Erdfelder, E., Faul, F., & Lang, A. (2009). G*Power (Version 3.1.7).

Canadian Institute for Health Information. (2007). Head InjuryThe Burden of Neurological Diseases, Disorders and Injuries in Canada. Ottawa: CIHI. Retrieved from https://secure.cihi.ca/free_products/BND_e.pdf.

Cantu, R. C. (1998). Second-impact syndrome. *Clinical Journal of Sports Medicine, 17*(1), 37-44.

Cantu, R. C., & Gean, A. D. (2010). Second-impact syndrome and a small subdural hematoma: An uncommon catastrophic result of repetitive head injury with characteristic imaging appearance. *Journal of Neurotrauma, 27*(9), 1557-1564.

Cantu, R. C., & Hyman, M. (2012a). Baseline Testing *Concussions and Our Kids*. New York: Houghton Mifflin Harcourt Publishing Co. .

Cantu, R. C., & Hyman, M. (2012b). Myths *Concussions and Our Kids*. New York: Houghton Mifflin Harcourt Publishing Co. .

Cantu, R. C., & Hyman, M. (2012c). What Is A Concussion? *Concussions and Our Kids*. New York: Houghton Mifflin Harcourt Publishing Co.

Carney, N., Ghajar, J., Jagoda, A., Bedrick, S., Davis-O'Reilly, C., du Coudray, H., . . . Riggio, S. (2014). Concussion guidelines step 1: Systematic review of prevalent indicators. *Neurosurgery, 75*(3), S3-S15.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale, NJ: Lawrence Earlbaum Associates.

Colantonio, A., Saverino, C., Zagorski, B., Swaine, B., Lewko, J., Jaglal, S., & Vernich, L. (2010). Hospitalizations and Emergency Department Visits for TBI in Ontario. *The Canadian Journal of Neurological Sciences, 37*(6), 783-790.

Collie, A., Darby, D., & Maruff, P. (2001). Computerised cognitive assessment of athletes with sprots related head injury. *Br J Sports Med, 35*, 297-302.

Concussion in Sport Group. (2013a). Child SCAT3. *Br J Sports Med, 47*(5), 263-266.

Concussion in Sport Group. (2013b). Pocket CRT (Concussion Recognition Tool). *Br J Sports Med, 47*, 267.

Croall, I. D., Cowie, C. J. A., He, J., Peel, A., Wood, J., Aribisala, B. S., . . . Blamire, A. M. (2014). White matter correlates of cognitive dysfunction after mild traumatic brain injury. *Neurology*, Advance online publication. doi: 10.1212/WNL.0000000000000666

Delaney, J. S., Lacroix, V. J., Leclerc, S., & Johnston, K. M. (2000). Concussions during the 1997 Canadian Football League season. *Clinical Journal of Sports Medicine, 10*(1), 9-14.

Dennis, M. (1988). Language and the young damaged brain. In T. Boll & B. K. Bryant (Eds.), *The master lecture series: Clinical neuropsychology and brain function: Research measurement and practice* (pp. 89-123). Washington, DC: American Psychological Association.

Dick, R. W. (2009). Is there a gender difference in concussion incidence and outcomes? *Br J Sports Med, 43 Suppl 1*, i46-50. doi: 10.1136/bjsm.2009.058172

Echemendia, R. J., Iverson, G. L., McCrea, M., Macciocchi, S. N., Gioia, G. A., Putukian, M., & Comper, P. (2013). Advances in neuropsychological assessment of sport-related concussion. *British Journal of Sports Medicine, 47*, 294-298.

Eckner, J. T., Oh, Y. K., Joshi, M. S., Richardson, J. K., & Ashton-Miller, J. A. (2014). Effect of Neck Muscle Strength and Anticipatory Cervical Muscle Activation of Kinematic Response of the Head to Impulsive Loads. *American Journal of Sports Medicine, 42*(3), 566-576. doi: 10.1177/0363546513517869

Elbin, R. J., Schatz, P., & Covassin, T. (2011). One-year test-retest reliability of the online version of ImPACT in high school athletes. *American Journal of Sports Medicine, 39*(11), 2319-2324.

Evans, M. (Producer). (2011, July 20, 2014). Concussions 101, a Primer for Kids and Parents. [Video] Retrieved from http://www.youtube.com/watch?v=zCCD52Pty4A

Ewing-Cobbs, L., Barnes, M., Fletcher, J. M., Levin, H. S., Swank, P., & Song, J. (2004). Modeling of longitudinal academic achievement scores after pediatric traumatic brain injury. *Developmental Neuropsychology, 25*(1-2), 107-133.

Ewing-Cobbs, L., Prasad, M. R., Kramer, L., Cox, C. S., Baumgartner, J., Fletcher, S., . . . Swank, P. (2006). Late intellectual and academic outcomes following traumatic brain injury sustained during early childhood. *Journal of Neurosurgery, 105*(Suppl 4), 287-296.

Ewing-Cobbs, L., Prasad, M. R., Landry, S. H., Kramer, L., & DeLeon, R. (2004). Executive functions following traumatic brain injury in young children: A preliminary analysis. *Developmental Neuropsychology, 26*(1), 487-412.

Fay, T. B., Yeates, K. O., Taylor, H. G., Bangert, B., Dietrich, A., Nuss, K. E., . . . Wright, M. (2009). Cognitive reserve as a moderator of postconcussive symptoms in children with complicated and uncomplicated mild traumatic brain injury. *Journal of the International Neuropsychological Society, 16*(1), 94-105.

Field, M., Collins, M. W., Lovell, M. R., & Maroon, J. (2003). Does age play a role in recovery from sports-related concussion? A comparison of high school and collegiate athletes. *The Journal of Pediatrics, 142*(5), 546-553.

Finch, C., McIntosh, A. S., McCrory, P., & Zazryn, T. (2003). A pilot study of the attitudes of Australian Rules footballers towards protective headgear. *Journal of Science and Medicine in Sport, 6*(4), 505-511.

Fletcher, J. M., Ewing-Cobbs, L., Francis, D. J., & Levin, H. S. (1995). *Variability in outcomes after traumatic brain injury in children: A developmental perspective*. New York, NY: Oxford University Press.

Friedland, D. (2013). Improving the classification of traumatic brain injury: The Mayo classification system for traumatic brain injury severity. *The Spine Journal, S4*. doi: 10.4172/2165-7939.S4-005

Friedland, D., & Hutchinson, P. (2013). Classification of Traumatic Brain Injury. *Advances in Clinical Neuroscience & Rehabilitation*.

Ganesalingam, K., Yeates, K. O., Ginn, M. S., Taylor, H. G., Dietrich, A., Nuss, K. E., & Wright, M. (2008). Family burden and parental distress following mild traumatic brain injury in children and its relationship to post-concussive symptoms. *Journal of Pediatric Psychology, 33*(621-629).

Gavett, B. E., Stern, R. A., & McKee, A. C. (2011). Chronic traumatic encephalopathy: A potential late effect of sport-related concussive and subconcussive head trauma. *Clinical Journal of Sports Medicine, 30*(1), 179-xi.

Gerberich, S. G., Priest, J. D., Boen, J. R., Straub, C. P., & Maxwell, R. E. (1983). Concussion incidences and severity in secondary school varsity football players. *American Journal of Public Health, 73*(12), 1370-1375.

Gioia, G. A. (2012). Pediatric Assessment and Management of Concussions. *Pediatric Annals, 41*(5), 198-203.

Gioia, G. A., & Collins, M. W. (2006). Acute Concussion Evaluation'Heads Up: Brain inury in your practice' tool kit developed by the Centers for Disease Control and Prevention (CDC). Retrieved from http://www.cdc.gov/ncipc/tbi/Physicians_Tool_Kit.htm.

Gioia, G. A., Collins, M. W., & Isquith, P. K. (2008). Improving identification and diagnosis of mild traumatic brain injury with evidence: Psychometric support for the acute concussion evaluation. *Journal of Head Trauma Rehabilitation, 23*(4), 230-242.

Gioia, G. A., Isquith, P. K., Guy, S. C., & Kenworthy, L. (2000). *Behaviour Rating Inventory of Executive Function*. Odessa, FL: Psychological Assessment Resources.

Gioia, G. A., Isquith, P. K., Schneider, J. C., & Vaughan, C. G. (2009). New approaches to assessment and monitoring of concussion in children. *Topics in Language Disorders, 29*(3), 266-281.

Gioia, G. A., & Mihalik, J. P. (2012). Concussion Recognition & Response: Coach and Parent Version: Psychological Assessment Resources, Inc.

Gioia, G. A., Schneider, J. C., Vaughan, C. G., & Isquith, P. K. (2009). Which symptom assessments and approaches are uniquely appropriate for paediatric concussion? *Br J Sports Med, 43 Suppl 1*, i13-22. doi: 10.1136/bjsm.2009.058255

Giza, C. C., & Hovda, D. A. (2001). The neurometabolic cascade of concussion. *Journal of Athletic Training, 36*(3), 228-235.

Greenwald, B. D., Burnett, D. M., & Miller, M. A. (2003). Brain injury: Epidemiology and pathophysiology. *Archives of Physical Medicine and Rehabilitation, 84*(S1), S3-7. doi: 10.1053/apmr.2003.50052

Gronwall, D., Wrightson, P., & McGinn, V. (1997). Effect of mild head injury during the preschool years. *Journal of the International Neuropsychological Society, 3*(6), 592-597.

Grundl, P. D., Biagas, K. V., Kochanek, P. M., Schiding, J. K., Barmada, M. A., & Nemoto, E. M. (1994). Early cerebrovascular response to head injury in immature and mature rats. *Journal of Neurotrauma, 11*(2), 135-148.

Guskiewicz, K., McCrea, M., Marshall, S. W., Cantu, R. C., Randolph, C., Barr, W., . . . Kelly, J. P. (2003). Cumulative effects associated with recurrent concussion in collegiate football players: the NCAA Concussion Study. *JAMA, 290*(19), 2549-2555.

Halstead, M. E., McAvoy, K., Devore, C. D., Carl, R., Lee, M., Logan, K., . . . Council on School, H. (2013). Returning to learning following a concussion. *Pediatrics, 132*(5), 948-957. doi: 10.1542/peds.2013-2867

Holbourn, A. H. S. (1943). Mechanics of Head Injuries. *The Lancet, 242*(6267), 438-441.

Hugenholtz, H., & Richard, M. T. (1982). Return to athletic competition following concussion. *Canadian Medical Association Journal, 127*(9), 827-829.

ImPACT Applications. (2011). *Technical Manual: Online ImPACT 2007-2012*: ImPACT Applications.

ImPACT Applications. (2014). About ImPACT. 2014, from https://http://www.impacttest.com/about/

Institute of Medicine of the National Academies. (2013). Sports-related concussions in youth: Improving the science, changing the culture. In N. A. o. Sciences (Ed.), (pp. 4). Washington, DC.

Iverson, G. L., Brooks, B. L., Collins, M. W., & Lovell, M. R. (2006). Tracking neuropsychological recovery following concussion in sport. *Brain Inj, 20*(3), 245-252. doi: 10.1080/02699050500487910

Iverson, G. L., Lovell, M. R., & Collins, M. W. (2003). Interpreting Change on ImPACT Following Sport Concussion. *Clin Neuropsychol, 17*(4), 460-467.

Jake Snakenberg Youth Concussion Act, 11-040, Colorado Senate (2012).

Karlin, A. M. (2011). Concussion in the pediatric and adolescent population: "different population, different concerns". *PM R, 3*(10 Suppl 2), S369-379. doi: 10.1016/j.pmrj.2011.07.015

Kaufman, Y., Tzischinsky, O., Epstein, R., Etzioni, A., Lavie, P., & Pillar, G. (2001). Long-term sleep disturbances in adolescents after minor head injury. *Pediatric Neurology, 24*(2), 129-134.

Kaut, K. P., DePompei, R., Kerr, J., & Congeni, J. (2003). Reports of head injury and symptom knowledge among college athletes: Implications for assessment and educational intervention. *Clinical Journal of Sports Medicine, 13*(4), 213-221.

Kegel, N. E., & Lovell, M. R. (2012). Methods of Formal Neurocognitive Assessment of Concussion. In J. N. Apps & K. D. Walter (Eds.), Pediatric and Adolescent Concussion: Diagnosis, Management and Outcome (pp. 117-131): Spinger Science+Business Media. doi: 10.1007/978-0-387-89545-1_10

Khurana, V. G., & Kaye, A. H. (2012). An overview of concussion in sport. *J Clin Neurosci, 19*(1), 1-11. doi: 10.1016/j.jocn.2011.08.002

Kirkwood, M. W., Yeates, K. O., & Wilson, P. E. (2006). Pediatric sport-related concussion: A review of the clinical management of an oft-neglected population. *Pediatrics, 117*(4), 1359-1371.

Knudson, D. (2007). Linear and Angular Kinematics *Fundamentals of Biomechanics* (2 ed., pp. 107-132).

Kroshus, E., Garnett, B., Hawrilenko, M., Baugh, C. M., & Calzo, J. P. (2015). Concussion under-reporting and pressure from coaches, teammates, fans, and parents. *Social Science & Medicine, 134*, 66-75. doi: http://dx.doi.org/10.1016/j.socscimed.2015.04.011

Kutcher, S. (2015). *Brain Injury Guide for Youth A guide to help you understand the effects of brain injury* Retrieved from http://www.teenmentalhealth.org

Lee, M. A., & Perriello, V. A. (2009). Adolescent concussions: Management guidelines for schools. *Connecticut Medicine, 73*(3), 171-173.

Lovell, M. R., & Collins, M. W. (2002). *ImPACT: The Best Approach to Concussion Management, Version 2.1 User's Manual*. Pittsburgh, PA.

Lovell, M. R., Collins, M. W., Podell, K., Powell, J. W., & Maroon, J. (2007). *ImPACT: Immediate post-concussion assessment and cognitive testing*. Pittsburgh, PA: NeuroHealth Systems, LLC.

Lovell, M. R., & Fazio, V. (2008). Concussion management in the child and adolescent athlete. *Current Sports Medicine Reports, 7*(1), 12-15.

Maddocks, D., Dicker, G. D., & Saling, M. M. (1995). The assessment of orientation following concussion in athletes. *Clinical Journal of Sports Medicine, 5*(1), 32-33.

Majerske, C. W., Mihalik, J. P., Ren, D., Collins, M. W., Reddy, C. C., Lovell, M. R., & Wagner, A. K. (2008). Concussion in sports: Postconcussive activity levels, symptoms, and neurocognitive performance. *Journal of Athletic Training, 43*(3), 265-274.

Malec, J. F., Brown, A. W., Leibson, C. L., Flaada, J. T., Mandrekar, J. N., & et al. (2007). The Mayo Classification System for Traumatic Brain Injury Severity. *Journal of Neurotrauma, 9*, 1417-1424.

Maugans, T. A., Farley, C., Altaye, M., Leach, J., & Cecil, K. M. (2012). Pediatric sports-related concussion produces cerebral blood flow alterations. *Pediatrics, 129*(1), 28-37. doi: 10.1542/peds.2011-2083

Mayers, L. B., & Redick, T. S. (2012). Clinical utility of ImPACT assessment for postconcussion return-to-play counseling: psychometric issues. *J Clin Exp Neuropsychol, 34*(3), 235-242. doi: 10.1080/13803395.2011.630655

McAvoy, K. (2013). *REAP* Retrieved from http://issuu.com/healthone/docs/reap_oct21/1

McCauley, S. R., Wilde, E. A., Barnes, A., Hanten, G., Hunter, J. V., Levin, H. S., & Smith, D. H. (2014). Patterns of Early Emotional and Neuropsychological

Sequelae after Mild Traumatic Brain Injury. *Journal of Neurotrauma, 31*, 914-925. doi: 10.1089/neu.2012.2826

McCrea, M. (2001). Standardized mental status testing of acute concussion. *Clinical Journal of Sports Medicine, 11*, 176-181.

McCrea, M., Guskiewicz, K., Marshall, S. W., Barr, W., Randolph, C., Cantu, R. C., . . . Kelly, J. P. (2003). Acute effects and recovery time following concussion in collegiate football players: the NCAA concussion study. *JAMA, 290*(19), 2556-2563.

McCrea, M., Hammeke, T., Olsen, G., Leo, P., & Guskiewicz, K. (2004). Unreported concussion in high school football players: Implications for prevention. *Clinical Journal of Sports Medicine, 14*(1), 13-17.

McCrory, P., Collie, A., Anderson, V., & Davis, G. (2004). Can we manage sport related concussion in children the same as in adults? *Britsh Journal of Sports Medicine, 38*, 516-519. doi: 10.1136/bjsm.2004.014811

McCrory, P., Davis, G., & Makdissi, M. (2012). Second impact syndrome or cerebral swelling after sporting head injury. *Current Sports Medicine Reports, 11*(1), 21-23.

McCrory, P., Meeuwisse, W. H., Aubry, M., Cantu, B., Dvorak, J., Echemendia, R. J., . . . Turner, M. (2013). Consensus statement on concussion in sport: the 4th International Conference on Concussion in Sport held in Zurich, November 2012. *Br J Sports Med, 47*(5), 250-258. doi: 10.1136/bjsports-2013-092313

McKee, A. C., Cantu, R. C., Nowinski, C. J., Hedley-Whyte, E. T., Gavett, B. E., Budson, A. E., . . . Stern, R. A. (2009). Chronic traumatic encephalopathy in athletes: Progressive tauopathy following repetitive head injury. *Journal of Neuropathology & Experimental Neurology, 68*(7), 709-735.

McKinlay, A. (2010). Controversies and outcomes associated with mild traumatic brain injury in childhood and adolescences. *Child: care, health and development, 36*(1), 3-21.

Meehan, W. P., & Bachur, R. G. (2009). Sport-related concussion. *Pediatrics, 123*, 114-123. doi: 10.1542/peds.2008-0309

Meehan, W. P., d'Hemecourt, P., Collins, C. L., Taylor, A. M., & Comstock, R. D. (2012). Computerized neurocognitive testing for the management of sport-related concussions. *Pediatrics, 129*(1), 38-44.

Meehan, W. P., Taylor, A. M., & Proctor, M. (2011). The Pediatric Athlete: Younger Athletes with Sport-Related Concussion. *Clinical Journal of Sports Medicine, 30*(1), 133-x. doi: 10.1016/j.csm.2010.08.004.

Mihalik, J. P. (2012). Biomechanics of sports concussion. In M. W. Kirkwood & K. O. Yeates (Eds.), *Mild Traumatic Brain Injury in Children And Adolescents: From Basic Science to Clinical Management*. New York: The Guildford Press.

Mild Traumatic Brain Injury Committee of the Head Injury Interdisciplinary Special Interest Group of the American Congress of Rehabilitation Medicine. (1993). Definition of mild traumatic brain injury. *Journal of Head Trauma Rehabilitation, 8*(3), 86-87.

National Strategy for Serious Injury Reduction in Amateur Sport Act, C-319 (2013).

NIH Consensus Developmental Panel on Rehabilitation of Persons with Traumatic Brain Injury. (1999). Rehabilitation of persons with traumatic brain injury. *Journal of the American Medical Association, 282*, 974-981.

O'Brien, L. M. (2009). The neurocognitive effects of sleep disruption in children and adolescents. *Child & Adolescent Psychiatric Clinics of North America, 18*(4), 813-823.

Omalu, B. I., Bailes, J., Hammers, J. L., & Fitzsimmons, R. P. (2010). Chronic traumatic encephalopathy, suicides and parasuicides in professional American athletes: The role of the forensic pathologist. *American Journal of Forensic Medicine & Pathology, 31*(2), 130-132.

Ommaya, A. K., Goldsmith, W., & Thibault, L. (2002). Biomechanics and neuropathology of adult and pediatric head injury. *British Journal of Neurosurgery, 16*(3), 220-242.

Ono, K., Kikuchi, A., Nakamura, M., Kobayashi, H., & Nakamura, N. (1980). Human head tolerance to sagittal impact: Reliable estimation deduced from experimental head injury using subhuman primates and human cadaver skulls *Proceedings of the 24th Stapp Car Crash Conference* (pp. 101-160). Warrendale, PA: Society for Automotive Engineers.

Ontario Ministry of Education. (2014). School Board Policies on Concussion. http://www.edu.gov.on.ca/extra/eng/ppm/158.pdf

Ontario Neurotrauma Foundation. (2014). Guidelines for Diagnosing and Managing Pediatric Concussion (1 ed.). Toronto, ON.

Patel, D. R. (2006). Managing concussion in a young athlete. *Contemporary Pediatrics, 23*(11), 62-69.

Pickett, W., Simpson, K., & Brison, R. J. (2004). Rates and external causes of blunt head trauma in Ontario: Analysis and review of Ontario Trauma Registry datasets. *Chronic Diseases in Canada, 25*(1), 32-41.

Powell, J. W., & Barber-Foss, K. D. (1999). Traumatic brain injury in high school athletes. *Journal of the American Medical Association, 282*(10), 958-963.

Protecting Student Athletes from Concussions Act of 2011, H.R. 469 (2011).

Purcell, L. (2009). What are the most appropriate return-to-play guidelines for concussed child athletes? *Br J Sports Med, 43 Suppl 1*, i51-55. doi: 10.1136/bjsm.2009.058214

Ransom, D. M., Vaughan, C. G., Pratson, L., Sady, M. D., McGill, C. A., & Gioia, G. A. (2015). Academic Effects of Concussion in Children and Adolescents. *Pediatrics, 135*(6), 1043-1050. doi: 10.1542/peds.2014-3434

Resch, J. E., McCrea, M. A., & Cullum, C. M. (2013). Computerized Neurocognitive Testing in the Management of Sport-Related Concussion: An Update. *Neuropsychology Review, 23*(4), 335-349. doi: 10.1007/s11065-013-9242-5

Rousson, V., Gasser, T., & Seifert, B. (2002). Assessing intrarater, interrater and test-retest reliability of continuous measurements. *Statistics in Medicine, 21*(22), 3431-3446.

Sady, M. D., Vaughan, C. G., & Gioia, G. A. (2011). School and the concussed youth - Recommendations for concussion education and management. *Physical Medicine & Rehabilitation Clinics of North America, 22*(4), 701-719. doi: 10.1016/j.pmr.2011.08.008

Schatz, P. (2009). Long-term test-retest reliability of baseline cognitive assessments using ImPACT. *American Journal of Sports Medicine, 38*(1), 47-53.

Schatz, P. (2010). Long-term test-retest reliability of baseline cognitive assessments using ImPACT. *Am J Sports Med, 38*(1), 47-53. doi: 10.1177/0363546509343805

Schatz, P., & Ferris, C. S. (2013). One-month test-retest reliability of the ImPACT test battery. *Archives of Clinical Neuropsychology, 28*(5), 499-504.

Schatz, P., & Maerlender, A. (2013). A two-factor theory for concussion assessment using ImPACT: Memory and speed. *Archives of Clinical Neuropsychology, 28*(8), 791-797.

Shenton, M. E., Hamoda, H. M., Schneiderman, J. S., Bouix, S., Pasternak, O., Rathi, Y., . . . Zafonte, R. (2012). A review of magnetic resonance imaging and diffusion tensor imaging findings in mild traumatic brain injury. *Brain Imaging and Behavior, 6*(2), 137-192. doi: 10.1007/s11682-012-9156-5

Statistics Canada. (2013). Appendix 4: Part of body affected by the most serious injury, among people who sustained at least one activity-limiting injury during the past 12 months, population aged 12 and over, Canada, 2009-2010. *Canadian Community Health Survey - Annual Component. 2009-2010 Combined.* Retrieved May 21, 2014, from http://www.statcan.gc.ca/pub/82-624-x/2011001/article/app/11506-04-app4-eng.htm

Tator, C. H. (2012). Sport Concussion Education and Prevention. *Journal of Clinical Sport Psychology, 6*, 293-301.

Teasdale, G., & Jennett, B. (1974). Assessment of coma and impaired consciousness: A practical scale. *Lancet, 2*, 81-84.

Tham, S. W., Palermo, T. M., Vavilala, M. S., Wang, J., Jaffe, K. M., Koepsell, T. D., . . . Rivara, F. P. (2012). The Longitudinal Course, Risk Factors, and Impact of Sleep Disturbances in Children with Traumatic Brain Injury. *Journal of Neurotrauma, 29*, 154-161. doi: 10.1089/neu.2011.2126

Thomas, D. G., Apps, J. N., Hoffmann, R. G., McCrea, M., & Hammeke, T. (2015). Benefits of Strict Rest After Acute Concussion: A randomized controlled trial. *Pediatrics, 155*(2), 1-11.

Valovich McLeod, T., & Gioia, G. A. (2010). Cognitive rest: The often neglected aspect of concussion management. *Athletic Therapy Today, 15*(2), 1-3.

Van Kampen, D. A., Lovell, M. R., Pardini, J. E., Collins, M. W., & Fu, F. H. (2006). The "valued added" of neurocognitive testing after sports-related concussion. *American Journal of Sports Medicine, 34*(10), 1630-1635.

Varni, J. W., Burwinkle, T. M., & Szer, I. S. (2004). The PedsQL Multidimensional Fatigue Scale in pediatric rheumatology: Reliability and validity. *Journal of Rheumatology, 31*, 2494-2500.

Weir, J. P. (2005). Quantifying Test-Retest Reliability Using the Intraclass Correlation Coefficient and the SEM. *Journal of Strength and Conditioning Research, 19*(1), 231-240.

Wilde, E. A., McCauley, S. R., Hanten, G., Avci, G., Ibarra, A. P., & Levin, H. S. (2012). History, Diagnostic Considerations, and Controversies. In M. W. Kirkwood & K. O. Yeates (Eds.), *Mild Traumatic Brain Injury in Children and Adolescents: From Basic Science to Clinical Management*. New York: The Guildford Press.

World Health Organization. (1992). *The ICD-10 classification of mental and behavioural disorders: Clinical descriptions and diagnostic guidelines.* Geneva: World Health Organization.

Yeates, K. O. (2010). Mild Traumatic Brain Injury and Postconcussive Symptoms in Children and Adolescents. *Journal of the International Neuropsychological Society, 16*(6), 953-960. doi: 10.1017/S1355617710000986.

Yeates, K. O., & Taylor, H. G. (2005). Neurobehavioural outcomes of mild head injury in children and adolescents. *Pediatric Rehabilitation, 8*(1), 5-16.

Zhang, L., Yang, K. H., & King, A. I. (2004). A proposed injury threshold for mild traumatic brain injury. *Journal of Biomechanical Engineering, 126*(2), 226-236.

Zuspan, S. J. (2013). Pediatric Concussion [Webinar]: Society of Trauma Nursing.

APPENDICES

APPENDIX A – Participant Screening Questionnaire

Basic Information

The items in this questionnaire address issues pertaining to your child's developmental history and family background. For questions that include numbered choice options, please select the number(s) that best describes your child and/or family. Other items will provide you with space(s) to provide a written response. Be sure to read each item carefully, and direct any questions to a member of the research staff. Try to answer each item as best you can, however, if you feel uncomfortable with any question, you do not need to answer it. Please know that your answers will be kept completely confidential.

Your First Name:

Phone Number:

Email Address:

Your Relationship to Child:

Child's Name

Child's Gender

Child's Birthdate

Child's Age

Child's Grade

Child's Primary Language

Racial/Ethnic Background of Child

What is the highest grade you, the guardian, have completed?

Hx of Head Injury

Has the child ever had any kind of head injury?

If yes, what happened?

If yes, was there a loss of consciousness?

If yes, for how long (in minutes)

Has the child ever had a concussion?

If yes, how long ago was their last concussion?

If yes, how did it happen?

If yes, who diagnosed/noticed it?

If yes, in your opinion has your child fully healed from their concussion?

Developmental History

Has the child ever had a seizure?

If yes, specify type:

Has the child ever been diagnosed with any of the following (please check all that apply):

- Speech Language Disorder
- Hearing problems
- Vision problems
- Autism spectrum
- Oppositional Defiant Disorder / Conduct Disorder
- None apply

Has the child ever been diagnosed with ADHD?

If yes, who made the diagnosis of ADHD?

Learning History

Has the child ever been diagnosed with a learning disability?

If yes, what type?

Does the child have an Individual Education Plan (IEP)?

If yes, what is it for?

APPENDIX B – ImPACT Testing Session Instructions

Today we will be conducting a baseline test that will be useful in the event that you are suspected of having sustained a concussion. So, it is very important that you give your best effort when completing this test. This baseline test will enable us to know how well you can do, under normal conditions, and the data will be used as part of my research project. If during the next year, you are suspected of having a concussion, you can come back to the university within a few days of your injury to retake the test for comparison to your baseline level of functioning.

If you suspect that you have sustained a concussion, it is important that you let the coach and your parents know, so that they can check you out. Common symptoms of concussion include a headache, dizziness, foggy headedness, nausea, and confusion. If you have any of these or any other symptoms after taking a hit, it is in your best interest to let the coach or trainer know about them. If you do have a concussion, you should take it seriously, but there is no need to panic. Athletes who sustain a concussion recover quite rapidly. About 50% of athletes with a concussion recover within a few days, and about 90% recover within 10 days. Just make sure to tell your parents or coaches if you feel funny after falling or taking a hit. I will be emailing some resources about concussions to your parents, including a neat Youtube video that you should watch with them. Are there any questions before we begin?

We are going to ask you to do several things on the computer, after you complete a consent form. First, you will be asked some questions about how you are feeling – whether you are feeling any of the “symptoms” like headaches or trouble paying attention. Next, you will take a test to see how well you can learn and remember things, and how fast you can work. There are 6 parts to this test. At the start of each part, you will be shown how to do it. You will get to practice each part of the test before starting. You will also have to come back again in two weeks to redo this task.

I will now read the consent form out loud to you, then you will have to sign it if you agree to participate. *read child consent* Now that you have agreed to participate in the study, I will have to ask all of the parents to leave the room and wait in the classroom next door.

We will now complete the ImPACT. Please pay close attention to the instructions. Do your best on the practice to make sure you know how to do the test. Make sure you follow the instructions carefully. Put up your hand if you have any questions or issues and someone will come to you. The instructions may seem harder for some parts than others, so just remember to pay attention and try your best. Sometimes kids worry because they make mistakes and think that they are not doing well. Everyone makes mistakes on this test. That is normal. Just do the best that you can. Please complete the ImPACT quietly so as not to distract the other participants, distractions during the ImPACT can affect performance on the test. When you have completed the ImPACT, put up your hand and someone will come check your computer and then you will be able to leave.

APPENDIX C – Scatterplots of Outcome Variables

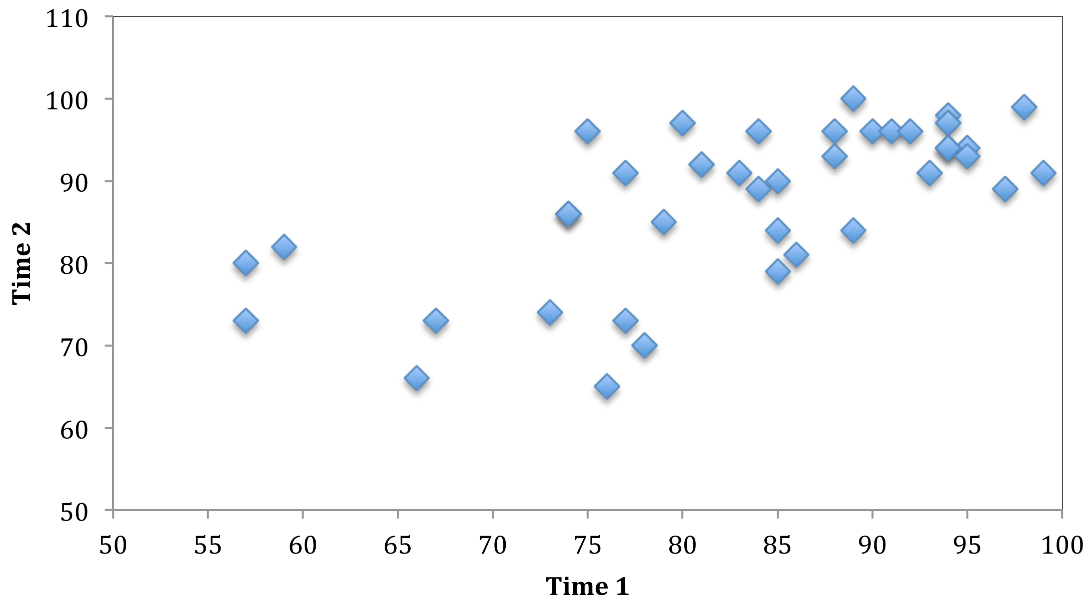

Figure 1. Scatterplot of the Verbal Memory scores at time 1 and 2.

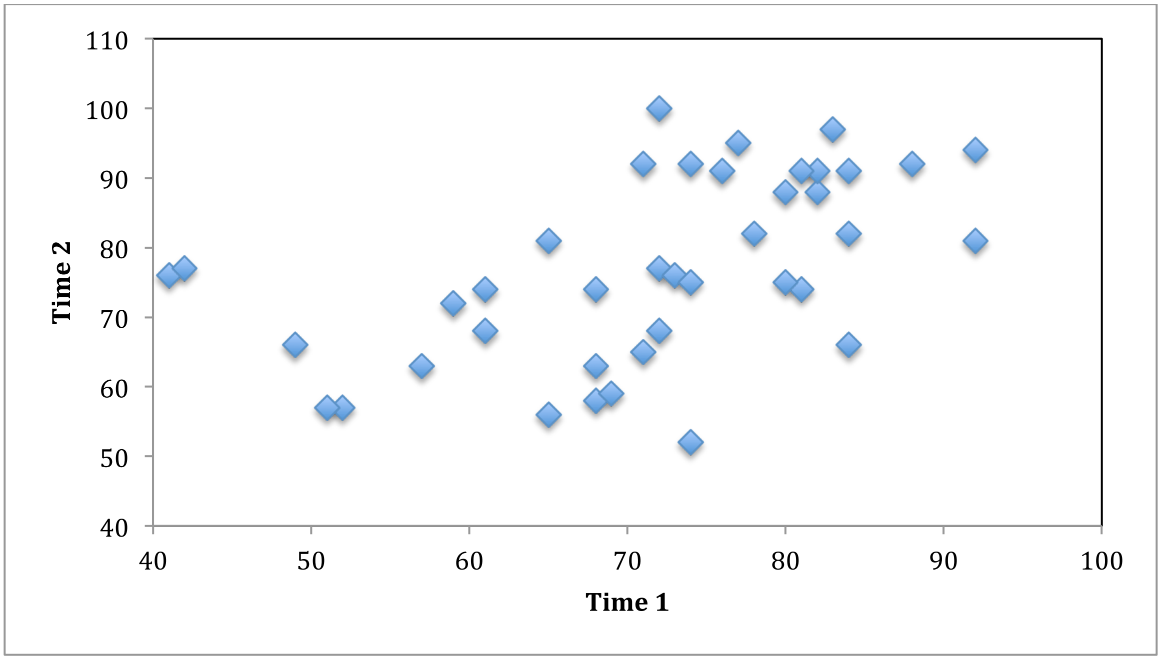

Figure 2. Scatterplot of the Visual Memory scores at time 1 and 2.

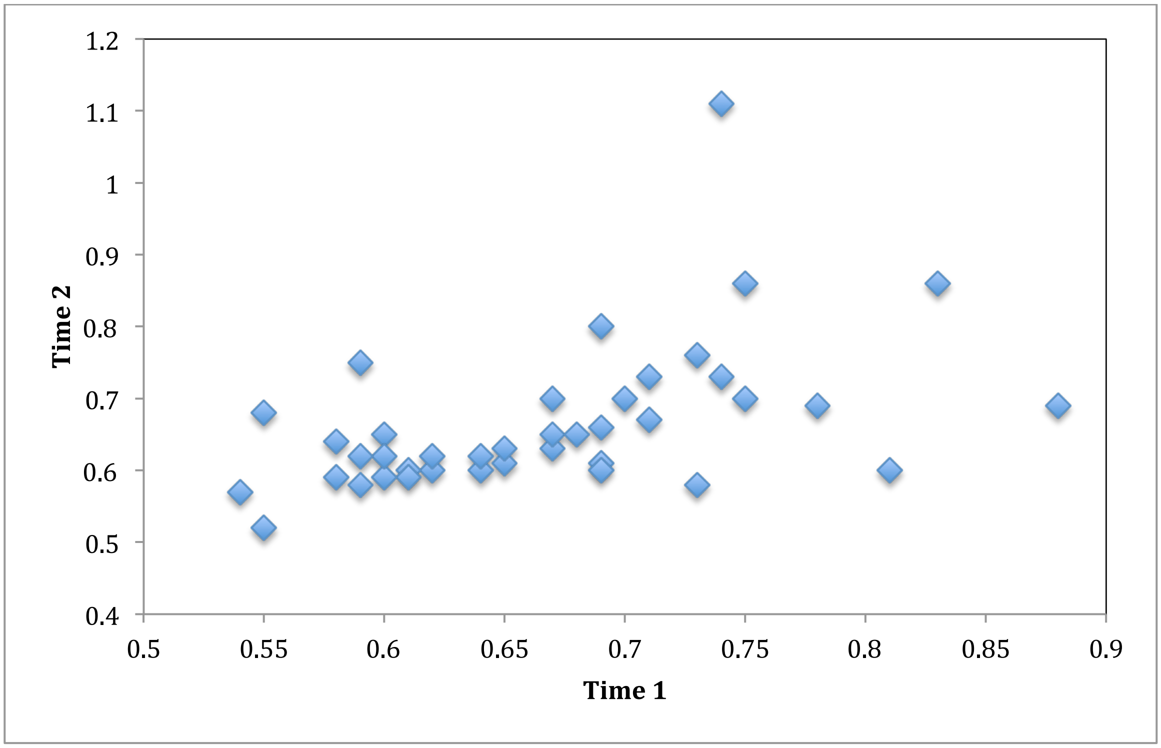

Figure 3. Scatterplot of the Reaction Time scores at time 1 and 2.

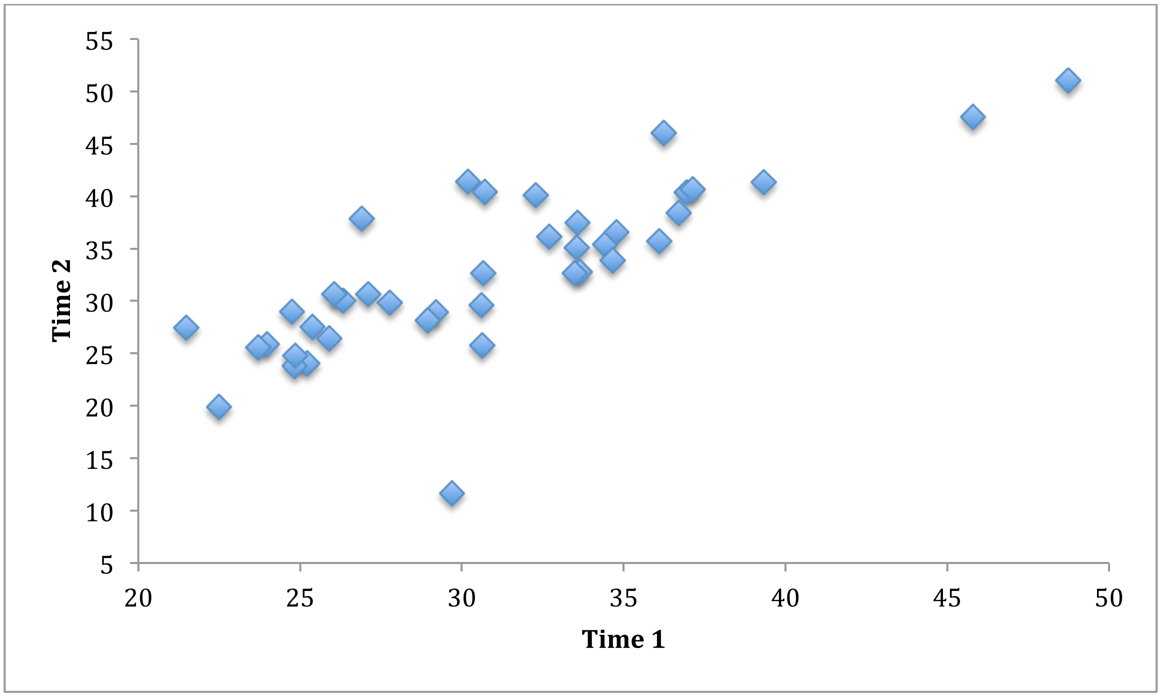

Figure 4. Scatterplot of the Visual-Motor Speed scores at time 1 and 2.

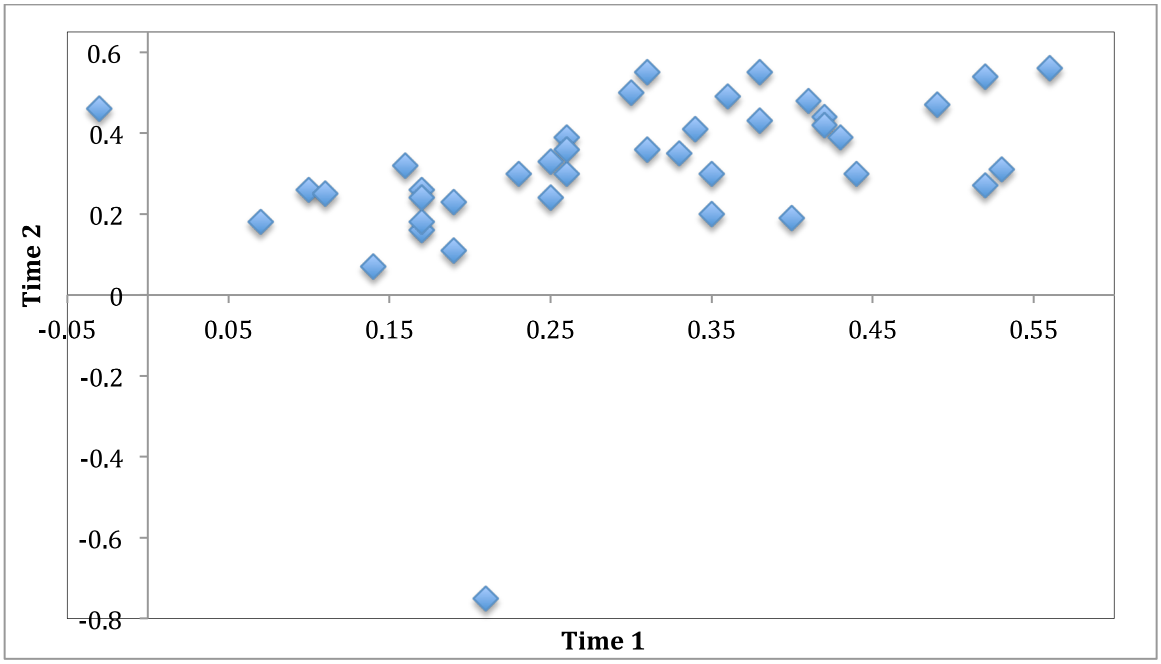

Figure 5. Scatterplot of the Cognitive Efficiency Index scores at time 1 and 2.

VITA AUCTORIS

NAME: Amanda Marion O’Brien

PLACE OF BIRTH: Windsor, Ontario

YEAR OF BIRTH: 1991

EDUCATION: Belle River District High School, Belle River, Ontario
2005-2009

University of Ottawa, Ottawa, Ontario
2009-2013, B.Sc.

University of Windsor, Windsor, Ontario
2013-2015, M.A.