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Validity of Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT)

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VALIDITY OF IMMEDIATE POST-CONCUSSION ASSESSMENT AND COGNTIVE TESTING (IMPACT)

DISSERTATION

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Clinical Psychology in the College of Arts and Sciences at the University of Kentucky

By

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ABSTRACT OF DISSERTATION

VALIDITY OF IMMEDIATE POST-CONCUSSION ASSESSMENT AND COGNTIVE TESTING (IMPACT)

Sports concussions have been recognized as significant injuries among young athletes with research demonstrating that return-to-play prior to becoming asymptomatic can have significant repercussions, including risk of sustaining cognitive deficits. In tracking and monitoring concussions during sports seasons, many programs have begun utilizing computerized testing rather than traditional neuropsychological tests to 1) determine baseline scores, 2) track symptoms, and 3) measure cognitive deficits following concussion.

Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) is one such instrument. The current study examined ImPACT's convergent, discriminant, and diagnostic validity by comparing scores from post-concussion athletes (SPORT) to those from non-concussed controls (CONT). SPORT included 29 athletes, ages 12-16, referred for neuropsychological testing following sports-related concussions. CONT included 25 healthy athletes, ages 12-16, who had not sustained a concussion in the past year.

Overall, results showed general support for ImPACT, when used to screen cognition. In fact, all ImPACT domains successfully differentiated between CONT and SPORT athletes; evidence supporting appropriate convergent validity was best for the Visual Memory domain. ImPACT domains demonstrated variable discriminant validity. Overall examination of validity demonstrated that ImPACT has some weaknesses but may have utility in detecting post-concussion cognitive impairment.

KEYWORDS*:* ImPACT, sports-related concussion, test validity, computerized measures, neurocognitive testing

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May 31, 2016___________
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CHAPTER 1: INTRODUCTION

Background

In recent years, increasing attention has focused on sports concussion with growing awareness of the injury and its potential consequences. Concussions, also known as mild traumatic brain injuries (mTBI), are insults to the brain that leave the individual briefly dazed or confused. If present, loss of consciousness is brief and typically lasts only seconds or minutes (National Institute of Neurological Disorders and Stroke, 2013). Unfortunately for reasons reviewed below, the exact prevalence of concussion is unclear. In an exceptionally wide interval, estimates of sports-related concussions range from 300,000 (CDC, 2007; Halstead, Walter, & The Council on Sports Medicine and Fitness, 2010) to 3.8 million annually (Langlois, Rutland-Brown, & Wald, 2006). The Center for Disease Control (CDC) estimated that 1.5 million people experience TBI yearly with 75% of those sustaining mTBI; an estimated 248,428 children under that age of 19 were treated in United States emergency departments for sports-related injuries, including concussions (National Center for Injury Prevention and Control, 2003). These estimates of sports concussions vary widely given inherent difficulty in tracking incidences. While emergency departments and medical providers document concussions well, many injuries do not require medical attention; suboptimal documentation in the field further complicates incidence and prevalence estimates. Individuals with the highest frequency of TBIs of all severity levels include males (2:1 ratio to females; Langlois, Rutland-Brown, & Thomas, 2004) and those aged between 0 to 4 years old or 15 to 19 years old (CDC, 2007; Langlois et al., 2004).

Although estimates vary widely, it is clear that sports concussions occur relatively frequently and impact the lives of many athletes. As such, doctors, athletic trainers, coaches, parents, and athletes have sought information to determine what symptoms are to be expected following concussion and their course. Historically, most attention has been paid to physical symptoms. An important and complicating issue is that both athletes and coaches typically desire quick return-to-play, a decision usually based on resolution of prominent physical symptoms. As recently as the early 2000's, concussed athletes were apt to return to play as soon as 15 minutes following symptom "resolution," better characterized as decreased acute physical symptoms (Halstead et al., 2010). However, in recent years research has begun to accumulate regarding the potentially significant sequelae and repercussions of sports-related concussions, further highlighting the need for quick assessment, intervention, and postponement of return-to-play as appropriate (e.g., Iverson et al., 2004; Macciocchi et al., 1996; McCrea et al., 2002, etc.).

Concussion Defined

Given the complexity of various symptom presentations with concussion, a number of definitions have been offered in an attempt to simplify and minimize subjectivity in diagnosing the condition. Operationalization definitions of concussion below show varying stringency, with some including broad, general criteria and others detailing specific symptom categories. The Center for Disease Control and Prevention (CDC) defines concussion as an injury with a Glasgow Coma Scale (GCS) score of 13 to 15 as well as the presence of one or more of the following: transient confusion, disorientation, or impaired consciousness; amnesia near time of injury; loss of consciousness (LOC) of less than 30 minutes; and/or neurological or neuropsychological problems including seizure, irritability, lethargy, emesis, headaches, dizziness, fatigue, or poor concentration (summarized in Rosenbaum & Lipton, 2012). The CDC's definition is quite broad, does not include subgroups/potential severity indicators, and does not define a period for posttraumatic amnesia, although specific symptom examples are presented.

Alternatively, the American Academy of Neurology (AAN) defines three grades of concussions. A Grade 1 concussion involves transient confusion and no LOC; any symptoms or mental status abnormalities resolve in less than 15 minutes (presented in Rosenbaum & Lipton, 2012). A Grade 2 concussion involves transient confusion with no LOC; positive symptoms or mental status abnormalities last longer than 15 minutes. Finally, Grade 3 concussions involve any LOC whether brief or prolonged with additional signs of concussion. It can be appreciated that the AAN definition is broader than the CDC version. However, it does not specify GCS or duration of LOC, although subgroups are defined.

Further complicating this situation, the most recent International Conference on Concussion in Sport in Zurich (McCrory et al., 2012) defined concussion as a brain injury with a "complex pathophysiological process affecting the brain, induced by biomechanical forces" (p. 1) and common features that "incorporate clinical, pathological, and biomechanical injury constructs" (McCrory et al., 2012, p. 1). McCrory et al. (2012) indicated the nature of concussions to be as follows: may be caused by direct blow to the head or body with force transmitted to the head; "typically resulting in rapid onset of short-lived impairment of neurological function that resolves spontaneously… in some cases, symptoms and signs may evolve over a number of minutes to hours" (p. 1); may result in neuropathological changes but typically are a "functional disturbance rather than a structural injury" (p. 1-2) leading to negative neuroimaging findings; and resulting in a "graded set of clinical symptoms that may or may not involve loss of consciousness" with recovery occurring in a sequential course in most cases but noting the potential for prolonged symptom recovery. Thus the Zurich guidelines offer an explanation of mechanism of injury and exclude abnormal neuroimaging findings but do not define a required period of LOC.

In a further attempt at operationalizing the phenomenon, Halstead et al. (2010) define sports-concussion as "a complex pathophysiological process affecting the brain, induced by traumatic biomechanical forces" (in Halstead et al., 2010, p. 598; McCrory et al., 2009) with five major features: 1. Caused by direct blow or transmitted force to the head, face, or neck; 2. Rapid onset of brief neurologic impairments; 3. Neuropathological changes often reflecting functional disturbance; 4. Clinical symptoms which may or may not include loss of consciousness; and 5. No abnormality on neuroimaging studies (Halstead et al., 2010). Considering the four definitions just presented, the Halstead et al. (2010) are the most detailed and stringent. However, this may lead to false negatives when following these guidelines.

Given the disagreement in published guidelines, it becomes clear that concussions are hardly an easily identifiable diagnostic category but instead may consist of a complex cluster of variable symptoms frequently co-occurring as a clinical syndrome. The lack of clear consensus in diagnostic guidelines introduces difficulty in identifying concussions, assessing symptoms, and tracking changes, leading to problems clinically and in research settings when addressing the condition.

Concussion Symptoms

Concussion symptoms are often broken into categories, albeit with the potential for overlap between each. As previously noted, many symptoms indicative of concussions have physical components or are related to somatic complaints. These include headache, nausea, vomiting, balance problems, visual problems, fatigue, sensitivity to light, and sensitivity to noise (Halstead et al., 2010). Other notable physical symptoms include those of neurasthenia (dizziness), weakness, and fatigue (Alves, Macciocchi, & Barth, 1993). Typically, physical complaints develop within 48 hours of the injury (Benedict et al., 2010). In documenting frequency of symptoms, Alves et al. (1993) found that in a sample of 587 adults with mTBI, headache was the most commonly endorsed problem following injury (50%); dizziness was the second most common complaint with a 15% endorsement rate. Other publications also support headache as the most common symptom following concussion (Halstead et al., 2010). Additional physical problems occurring with less frequency in concussion populations include amnesia and loss of consciousness (LOC), with approximately 10% of injuries resulting in positive loss of consciousness (Halstead et al., 2010) and up to 25% of concussions resulting in amnesia (Meehan, D'Hemecourt, & Comstock, 2010).

A second category of concussion symptoms includes cognitive disturbances that may be endorsed following concussion. These include feeling "foggy," decreased processing speed, difficulty concentrating, difficulty remembering (including feeling forgetful), and confusion (Halstead et al., 2010). Overall, the most common cognitive deficits following concussion are in the domains of short-term memory, processing speed, attention, and concentration (e.g., Bohnen, Jolles, & Twijnstra, 1992; Hinton-

Bayre et al., 1999; etc.). When present, cognitive symptoms typically develop within the first few weeks following the injury (Benedict et al., 2010) but usually remit after one to three months.

In addition to cognitive and physical complaints, emotional difficulties are also reported. These mood and/or emotional symptoms may include labile emotions, depression, anxiety, agitation, irritability, impulsivity, and aggression (Alves et al., 1993; Benedict et al., 2010). Halstead et al. (2010) noted that post-concussion emotional responses are similar to those described by patients with psychiatric diagnoses such as anxiety, depression, and/or attention/concentration difficulties. Further adding to the potential symptoms are possible sleep disturbances such as increased drowsiness, sleeping more often than usual, sleeping less often than usual, or difficulty falling asleep (Halstead et al., 2010). Behavioral and sleep difficulties may take longer than physical and cognitive complaints to develop, and may first arise as long as one to two months post-injury (Benedict et al., 2010).

Variability of Concussion Symptoms

While the physical, cognitive, and emotional symptoms just reviewed are common indicators of concussion, great heterogeneity exists regarding individual clinical presentations, symptom endorsement, symptom clusters, and the presence or absence of common specific symptoms. Temporally, a wide degree of variability exists in individual presentation, ranging from a brief, time-limited cluster of mainly physical symptoms to a longer, more pronounced presentation of physical, cognitive, and behavioral symptoms. For instance, AAN concussion guidelines indicate that Grade 1 concussions result in quick resolution of symptoms (under 15 minutes). This is directly contrasted to the lengthier and more complex presentation of symptoms in post-concussion syndrome. Some of the factors affecting heterogeneity of post-concussion symptom presentation are addressed next.

Factors Affecting Concussion Symptoms

A number of factors may contribute to the heterogeneity of concussion symptoms. Many of these factors are premorbid in nature such as age, gender, intelligence, socioeconomic factors, ethnicity, education, psychiatric history, personality, and substance abuse (Karzmark, Hall, & Englander, 1995; Rosenbaum & Lipton, 2012). As previously discussed, concussive injuries are bimodal as they occur most frequently in adolescents/young adults and older adults. As addressed in later sections, adolescents and young adults are more likely than other age groups to experience a longer recovery period when symptomatic. However, they also may be more likely to minimize reports of symptoms following sports-concussions given a propensity to remain "team players" and further maintain the social structure fostered by a competitive sports environment. Additionally, while the research indicates that males are more likely than females to sustain concussions, females are more likely to endorse post-concussion symptoms and to seek treatment for them (Rosenbaum & Lipton, 2012). The increased likelihood for males to sustain a concussion is directly reflected in the predominantly male literature. However, the lack of research pertaining to female subjects unfortunately makes it difficult to generalize research results to females. Further, social factors such as socioeconomic status, ethnicity, and obtained education level affect the presence and presentation of symptoms. Education and higher intelligence have been shown to be protective in nature (Rosenbaum & Lipton, 2012). As a result, individuals with better intellectual abilities may be less likely to experience cognitive and behavioral symptoms following concussion. This is especially true of intelligent individuals with no premorbid psychiatric history.

Each concussion is unique in that it occurs in a context of individual factors, with symptom presentation dependent on a combination of premorbid factors in conjunction with injury mechanisms and post-injury recovery variables. As a result, symptom presentation following concussion ranges from the absence of cognitive, physical, or emotional symptoms with a recovery window of a few minutes to the presence of a wide variety of cognitive, physical, and/or emotional symptoms lasting weeks or months. As a result of this heterogeneity, the complexity noted earlier in assessing and difficulty in tracking concussion symptoms and presentations should be less surprising. While many of the possible concussion symptoms are well-understood independently, research is currently attempting to understand interactions among them as well as the variability in symptom presentation.

Typical Recovery Course

While recovery from mTBI typically occurs relatively quickly (i.e., minutes to hours), as noted earlier large variations in symptom presentation and recovery course have been documented (e.g., Alves et al., 1993; Halstead et al., 2010). For instance, Halstead et al. (2010) reported that the majority of concussed individuals become asymptomatic within one week following injury. In contrast, Alves et al. (1993) longitudinally assessed adults with prolonged mTBI symptoms with the following percentages endorsing symptoms present at each interval: 40-60% at 3 months, 25-45% at 6 months, and 10-40% at 12 months. This pattern demonstrates that although the majority of individuals were symptom-free 6 months following injury; some had an atypical (i.e., longer) recovery course. In this regard, age may play an important role in recovery time with several studies demonstrating increased recovery time in younger athletes (e.g., Field, Collins, Lovell, & Maroon, 2003; Lovell, Collins, & Iverson, 2003; McClincy et al., 2006; McCrea et al., 2009; Pellman, Lovell, Viano, & Casson, 2006). In fact, these younger athletes are often symptomatic seven to ten days longer than their older counterparts. In addition, a major limitation in documenting typical recovery course involves failure to study individuals who do not seek medical attention and may recover in minutes to hours following concussion.

Variability in Recovery Course

There are several possible explanations that have been offered for the variability in symptom presentation and recovery course in concussion. Differences in underlying pathophysiological changes may variably disrupt neurological functioning, contributing to uneven development of impairments. Additionally, psychological difficulties may develop or worsen following concussion and may, along with preexisting psychological conditions, exacerbate concussion-related symptoms. Another factor affecting variability in recovery course is likely the number of previous concussions, with each successive concussion more likely to be problematic. Additionally, published research is often subtly skewed, with a bias towards scientific studies including longer recovery windows given the higher likelihood for those experiencing more persistent symptoms to present for treatment. As a result, those individuals who experience concussion with a brief symptomatic period followed by full recovery are not often represented in scientific studies. Finally, recommendations regarding cognitive and physical rest following concussion may affect recovery course. Each of these factors contributes to variability in recovery course and thus will be reviewed next in some detail.

Possible Pathophysiological Changes

Physiological factors may affect recovery from concussion. Complex pathophysiological changes secondary to concussion have been summarized by many researchers (e.g., Alves et al., 1993; Brown et al., 2014; Comper et al., 2010; Halstead et al., 2010; etc.). Seemingly small differences in the initial states of complex biological pathways could lead to substantial variability in outcomes. If microscopic pathophysiological damage is present it may not always be visible on neuroimaging, but changes such as ionic shifts, abnormal metabolism, diminished cerebral blood flow, and abnormal neurotransmission may occur following concussion, leading to functional impairment (Comper et al., 2010). However, some research suggests that measureable physiological changes may sometimes occur following concussion. Some magnetic resonance imaging studies point to potential macroscopic parenchymal lesions, often located in the frontal and temporal lobes (summarized in Alves et al., 1993). These tiny lesions resolve quickly and largely without medical intervention and may correspond to estimates of spontaneous recovery following concussion. Further, metabolic responses have been noted in animal models following concussions. These include disrupted cellular membranes, potassium efflux, and glutamate release that result in cellular depolarization and neuronal suppression (Halstead et al., 2010). This cascade of metabolic alterations can result in calcium accumulation, oxidative damage, and eventually cell death, with the disrupted metabolic state persisting up to four weeks following injury (Halstead et al., 2010). As summarized in Brown et al. (2015), additional pathophysiological changes that can result in prolonged recovery include ionic fluxes and increased need for adenosine triphosphate (ATP) coupled with post-concussive decrease in production of ATP. The likelihood of documenting physiological changes following concussion increases with injury severity. Several symptoms, such as positive loss of consciousness and amnesia, are indicators for increased severity of injury which often result in longer recovery time (Halstead et al., 2010). Additionally, mTBI can further exacerbate preexisting neurological conditions and associated physiological distress, which in turn may influence symptoms and recovery (Alves et al., 1993). However, a cautionary stance is required when attributing functional deficits and symptoms reports to the possibility of underlying pathophysiological changes as the presence of such changes has been documented in injuries with spontaneous recovery as well as injuries with prolonged symptom complaints.

Psychological and Other Factors

Psychological factors have also been found to contribute to symptom presentation and recovery course. For instance, Alves et al. (1993) noted that preexisting and/or comorbid somatoform disorders, mood disorders (i.e., anxiety, depression, etc.), and posttraumatic stress disorder can exacerbate concussion symptoms. Further, concussions in turn can exacerbate pre-existing psychological difficulties, including anxiety, depression, and attention-deficit disorder, making symptom management more difficult (Halstead et al., 2010). Additionally, although less well understood, patient expectancies regarding symptoms and duration may also affect overall outcomes and recovery course (Alves et al., 1993; Thomas et al., 2015). Some research indicates that persistent symptoms following concussion may be the result of expectations regarding injury, as well as poor coping styles and emotional reactions to adverse events (Bohnen & Jolles, 1992; Mittenberg, DiGulio, Perrin, & Bass, 1992). For example, individuals who are prone to focusing on somatic complaints, those who tend to ruminate anxiously, or those who focus on negative or depressive factors may be more likely to notice and complain of deficits following concussion. Similarly, individuals faced with diagnosis threat, or preexisting beliefs and fears regarding cognitive deficits following concussion, are likely to demonstrate decreased performances on neurocognitive measures following injury (Pavawalla et al., 2013).

Repeated Concussions and Second-Impact Syndrome

Cumulative concussions over time may also have a significant negative effect on recovery. Winston et al. (2016) demonstrated that in rat models a single mTBI did not result in permanent physiological changes; however, 30 mTBIs over a span of 7 days resulted in dendritic spine loss and chronic white matter inflammation. This factor is of particular concern, given that once athletes have suffered a concussion they are at increased risk for sustaining future concussions (Comper et al., 2010). Individuals with three or more concussions have been noted to exhibit more severe symptoms, including LOC and amnesia following subsequent concussion (Collins et al., 2002). As noted previously, severe symptoms may lengthen recovery course. Further, multiple concussions may be especially detrimental in younger athletes, affecting overall cognitive ability. For instance, athletes who had previously sustained and then recovered from two or more concussions were tested when currently asymptomatic. These asymptomatic athletes demonstrated similar performances to currently concussed (i.e., symptomatic) peers on neuropsychological tests; the athletes with cumulative concussions also demonstrated lower grade-point averages than their single-concussion and non-concussed peers (Moser, Schatz, & Jordan, 2005). While this research suggests occurrence of consecutive concussions in a short period of time may impair recovery, researchers have not established relevant parameters, such as number and severity of concussions over time, that are associated with problematic recovery.

For those individuals who have sustained previous concussions, timing of later concussions may also be a significant factor in severity of symptoms and overall recovery course. Specifically, additional concussions that occur while an individual is still symptomatic from a previous concussion can be particularly problematic. This second-impact syndrome can cause cerebral vascular congestion, which can in turn progress to cerebral swelling and ultimately death (Cantu & Voy, 1995; Halstead et al., 2010). Second-impacts during the recovery window may also lead to hemorrhaging if weak blood vessels are present. Fortunately, sudden impact syndrome is quite rare, with the CDC estimating 1.5 associated deaths per year and the National Alliance for Youth Sports estimating 6 to 7 associated deaths per year. While long-term effects following concussion are still disputed, it has become clear that increased number of concussions and successive concussions in a short time period negatively affect sequelae and recovery course.

Cognitive Rest

Although a period of rest following concussion has become standard practice, varying opinions exist regarding length of rest following concussion. This is exacerbated by a paucity of literature leading to lack of substantive and empirically-supported guidelines. Variability exists within the sparse literature, with some proponents espousing brief periods of cognitive rest and others favoring long periods of cognitive rest. For instance, some research supports periods of rest of one week or longer. Moser, Glatts, and Schatz (2012) reported that regardless of onset of cognitive and physical rest following concussion, rest length of one or more weeks has been shown to be effective in treating concussion symptoms; length of time between concussion and onset of rest was either 1 to 7 days, 8 to 30 days, or 31 or more days (Moser, Glatts, & Schatz, 2012). Additionally, Majerske et al. (2008) noted that athletes who engaged in high levels of activity following concussion exhibited worse neurocognitive performance when compared to lower activity level post-concussion participants. Brown et al. (2014) found that of those factors affecting recovery, only total symptom burden at initial visit and cognitive activity level were associated with duration of symptoms; post-injury cognitive rest significantly improved recovery. However, a growing literature base supports briefer rest periods and approaches extended rest cautiously given limited evidence of benefit to athletes. Gibson et al. (2013) indicated that a total of 135 concussed participants were examined with providers recommending rest for 85 participants. Of those 85 participants, 79 participants demonstrated prolonged symptoms. Thomas et al. (2015) compared participants ages 11 to 22 years old who were assigned to usual care (1 to 2 days rest with following stepwise return to activity) to participants assigned to strict rest for 5 days. Results demonstrated that participants in the strict rest group reported significantly more daily post-concussive symptoms and slower symptom resolution than those in the usual care group. Thus accumulating research raises the possibility of prolonged rest contributing to persistent difficulties following concussion. Currently, the International Conference on Concussion in Sport in Zurich (McCrory et al., 2012) guidelines note the paucity of empirical evidence for strict rest guidelines and indicate that while an initial one to two day rest period during the acute phase of recovery is likely beneficial, clinical judgment is best used to determine a gradual return to activities that “does not result in a significant exacerbation of symptoms” (p. 3).

Post-concussion Syndrome

Clearly, a number of factors are known to affect symptom severity and recovery, although most outcomes from concussion are excellent. However, in a small number of individuals, symptoms persist beyond the expected one to three month recovery period and can be debilitating. Such persistent presentations may meet criteria for post-concussion syndrome (PCS). The Diagnostic and Statistical Manual of Mental Disorders, Fourth Edition (DSM-IV-TR; American Psychiatric Association, 2000), included research criteria for a PCS diagnosis including “history of head trauma that has caused significant cerebral concussion” (p. 761), “evidence from neuropsychological testing or quantified cognitive assessment of difficulty in attention…or memory” (p. 761), and three or more of the following symptoms occurring shortly after the concussion and lasting three months or longer post-concussion: fatigue, disordered sleep (i.e., sleeping too little or too much), headache, vertigo, or dizziness, irritability/aggression, anxiety, depression, personality changes, and/or apathy. The most recent DSM-5 removed the PCS diagnosis and instead included criteria for either major or mild neurocognitive disorder due to traumatic brain injury with the ability to add “with behavioral disturbance” as a modifier (American Psychiatric Association, 2013). Despite this change in the DSM, many providers still acknowledge that PCS is a useful diagnosis to differentiate between individuals with typical recovery trajectories as compared to those with atypical recovery trajectories.

CHAPTER TWO: CONCEPTUAL DEVELOPMENT

Testing Following Concussion

Cognitive testing may be useful in order to track cognitive changes and symptom recovery post-concussion when such problems are reported. These evaluations may be given as early as minutes following injury. Sideline testing for sports-concussion often includes initial assessment of the “ABCs” (i.e., airway, breathing, and circulation), a brief functional neurologic assessment (i.e., evaluation of movement, pain, etc.), inquiry regarding symptoms, and brief evaluation of cognitive status (Halstead et al., 2010). These acute injury evaluations can be informal or assessed with several available tools, including Maddocks’ questions (Maddocks, Dicker, & Saling, 1995), Standardized Assessment of Concussion (SAC; McCrea et al., 1998), Balance Error Scoring System (BESS; Guskiewicz, 2003), or Sports Concussion Assessment Tool 3 (SCAT3; McCrory et al., 2012). Beyond sideline testing, follow-up medical intervention and further neuropsychological testing are warranted in some cases. Symptoms that warrant further medical intervention include “repeated vomiting, severe or progressively worsening headache, seizure activity, unsteady gait or slurred speech, weakness or numbness in the extremities… or altered mental status” (Halstead et al., 2010, p. 601). These symptoms may also be indicative of increased potential for cognitive deficits in the days or weeks following injury.

Cognitive testing has become increasingly popular as a method to track recovery when indicated, and as noted above many sports programs have implemented preseason baseline cognitive testing that can be compared to post-injury results. When baseline testing is in place, it typically consists of brief cognitive tests given to all players before the start of the season (Halstead et al., 2010). However, more severe cognitive changes warrant comprehensive evaluations. For example, neuropsychological testing may be appropriate for individuals who report or exhibit more persistent (i.e., longer than one week) cognitive deficits following injury. The assessment process serves as an objective measurement of cognitive functioning, can be used to document deficits, to inform regarding appropriateness of temporary accommodations in the school setting, and to assist in making return-to-play decisions.

Traditional Neuropsychological Testing

Formal neuropsychological evaluation following concussion was initiated by Barth in the early 1980's, when pre-season test scores were compared to post-concussion test scores in what has become the typical baseline framework (Comper et al., 2010). Traditional neuropsychological assessment following concussion often assesses a wide range of cognitive functions, including verbal memory, visual memory, processing speed, executive functions, attention, language expression and/or comprehension, and visuospatial functions. As noted previously, attention, short-term memory, and processing speed deficits are among the most commonly reported cognitive deficits following concussion. Traditional neuropsychological testing involves individualized assessment using paper-and-pencil tests supervised by a licensed neuropsychologist. While these traditional evaluations allow for in-depth and patient-specific testing, they have a number of disadvantages. Testing is lengthy and can only be done on an individual basis. Additionally, it may be difficult to get a short-notice appointment. Due to the short-lived nature of most concussion symptoms, many individuals may recover in the time it takes to get an assessment appointment. Such difficulties in using paper-and-pencil tests have led to expansion and inclusion of new testing formats. Computerized testing following concussion has become popular and may be included in a full neuropsychological battery for those individuals demonstrating persistent cognitive symptoms or may be used for preseason and post-concussion tracking. Examining the utility of such computerized measures has become a crucial step in determining the most appropriate tools for post-concussion assessment.

Computerized Testing

Computerized testing offers a number of benefits, including ease of use, suitability for large groups, and administration that may be supervised by a wide range of personnel (i.e., athletic trainer, coaches, physicians, etc.). Such accessibility and ease of use means that baseline testing has become routine in many sports programs, with athletes tested as a large group over a short period of time in a computer lab (Halstead et al., 2010). Due to a growing market for computerized testing, many companies are attempting to develop computerized tests that can be used for baseline and post-injury comparisons.

ImPACT

One such computerized cognitive testing tool that is increasing in popularity is Immediate Post-Concussion Assessment and Cognitive Testing, Version 3.0 (ImPACT; Lovell et al., 2005). ImPACT is a computerized neuropsychological testing battery consisting of 6 modules: Word Memory, Design Memory, X's and O's, Symbol Matching, Color Match, and Three Letter Memory (Lovell et al., 2005). The test taps several cognitive domains, including verbal memory, visual memory, attention, reaction time, impulse control, and response variability. ImPACT testing potentially offers many advantages, including ease of use, accessibility, decreased costs, and multi-domain assessment. The test is deemed suitable for administration by athletic trainers, school nurses, athletic directors, team physicians, and/or psychologists who have received appropriate training. Additionally, administration time is brief, approximately 20 minutes, and use of a computerized format facilitates mass baseline testing sessions (ImPACT, Applications Inc., 2013).

Research examining the utility of ImPACT and its validity as a neurocognitive testing tool is accumulating (i.e., Iverson, Brooks, Collins, & Lovell, in Press; Iverson, Lovell, & Collins, 2005; Schatz et al., 2006; etc.). For instance, Iverson, Lovell, and Collins (2005) compared ImPACT results from 72 amateur athletes to the same athletes' results from the Symbol Digit Modalities Test (SDMT) and demonstrated that ImPACT Processing Speed Composite and Reaction Time Composite correlated highly with SDMT results (r =.70, p <.01). Data were further examined via exploratory factor analysis, demonstrating that the Processing Speed composite, Reaction Speed Composite, and SDMT likely measure the same underlying construct (Iverson et al., 2005). Schatz et al. (2006) examined ImPACT's sensitivity and specificity to concussion in a group of 72 high school athletes tested within 72 hours of sustaining an injury. When concussed athletes were compared to non-concussed athletes, the former demonstrated significantly lower performances than non-concussed athletes on all ImPACT domains. Results further indicated a sensitivity rate of 81.9% and a specificity rate of 89.4%, although criteria for these sensitivity and specificity rates were unclear.

Additional evidence supports ImPACT's construct and convergent validity. Allen and Geller (2011) compared ImPACT to the traditional NFL cognitive battery and found a four-factor solution explaining 70% of the variance using the NFL battery and a five-factor solution explaining 69% of the variance using ImPACT. Factors were fairly comparable between the two batteries, although ImPACT demonstrated unique factors that likely involve executive function constructs. An additional study by Maerlender et al. (2010) also demonstrated adequate construct and convergent validity in comparing ImPACT's factor loadings to those of a traditional paper-and-pencil battery. Convergent validity was demonstrated for four of the five constructs. However, Maerlender et al. (2010) noted that ImPACT failed to assess sustained attention and auditory working memory, two domains that are commonly compromised by mTBI. The authors opined that ImPACT is a useful screening tool, but suggested that other sources of data are necessary to detect and manage concussions (Maerlender et al., 2010). In a follow-up study Maerlender et al. (2013) examined ImPACT's discriminant validity using a multi-trait mono-method approach. In doing so, ImPACT domain composite scores were correlated with the averaged linear combination of discriminant composites (Maerlender et al., 2013) using the formula T1 r [(T2 + T3 + T4)/3] in which T1 is the ImPACT domain T-score (e.g., Verbal Memory) and T2, T3, and T4 are T-scores of the other ImPACT domains (e.g., Visual Memory, Reaction Time, and Visual Motor Speed). Results demonstrated that three of the four domains share method variance with the following significant correlations: Visual Memory vs. ImPACT composite discriminant validity coefficient ($r = 0.423$; $p = 0.002$), Verbal Memory vs. discriminant validity coefficient ($r = 0.328$; $p = 0.017$), and Visual Motor Speed vs. discriminant validity coefficient ($r = 0.354$; $p = 0.010$). ImPACT Reaction Time demonstrated unique variance evidenced by a nonsignificant relationship with the discriminant validity coefficient (r =

0.117; *p* = 0.411; Maerlender et al., 2013). This multi-trait mono-method approach appears to be a promising method for evaluating discriminant validity.

Finally, sequential examination of performance using ImPACT demonstrates its potential utility as a tracking tool. Iverson et al. (2006) tracked 30 amateur athletes who had undergone pre-season baseline testing and sustained in-season concussions over the course of three evaluations: one to two days post injury, three to seven days post injury, and one to three weeks post injury. Results revealed significant decrements in performance (when compared to pre-season baselines) on five ImPACT composite domains during the first post-concussion testing. The majority of athletes' deficits largely resolved by 5 days post injury and fully resolved by 10 days post injury. Of note, 37% of the group demonstrated continued reporting of symptoms at the 10 day post injury evaluation (Iverson et al., 2006). Such research highlights the potential utility of using quick computerized measures to track symptomatology and course of recovery on an individual basis, allowing for more appropriate return-to-play decisions.

Outstanding Issues

Despite the accumulating research regarding ImPACT's validity and utility as a sports-concussion assessment tool, several issues have not been thoroughly addressed in the published literature. Most critically, there appears to be a lack of independent validation studies. Many of the existing studies have been conducted by researchers who share authorship on ImPACT or who develop research studies that are directly tied to ImPACT sales (i.e., validation studies appearing on the sales website). Thus, there is a need for further examination by independent researchers in order to cross-validate the test battery.

Another issue is that much of the research to date appears to be derived from samples that may be problematic in various ways. For instance, Schatz et al. (2006) did not exclude athletes from special education classes and athletes who had learning disabilities (LD). Rates of these individuals were higher in the concussed group than in the non-concussed group (3% special education, 3% LD in the concussed group vs. 2% special education, 1% LD in the control group). Additionally, many currently existing validation studies failed to exclude individuals with pre-existing psychological diagnoses such as anxiety, depression, attention deficit/hyperactivity disorder (ADHD), etc. Inclusion of individuals with premorbid psychological disorders poses several problems. As previously mentioned, psychological factors can impact both symptom presentation and recovery course, exacerbating cognitive deficits following concussion (Alves et al., 1993). Additionally, it remains possible that pre-existing psychological conditions may a priori increase the potential of sustaining a concussion due to factors such as decreased cognitive functions. Similarly, it is possible that psychological symptoms increase the likelihood of experiencing symptoms following a strike to the head (perhaps due to increased focus on somatic complaints). Due to cognitive repercussions of psychological disorders and potential for vulnerability to concussion symptoms, individuals with psychological disorders and/or educational difficulties (i.e., special education, LDs) should be excluded from validation studies in order to create homogenous samples that do not include possible cognitive confounds.

Another issue is that other published studies often involve comparison groups that may confound findings such as contrasting high-risk contact sports athletes with multiple previous concussions to low-risk noncontact sports athletes with no history of concussion (e.g., Schatz et al., 2006). At present, research has not confirmed comparability of cognitive and personality factors between contact sport athletes and non-contact sport athletes; it remains possible that premorbid differences may exist between such groups. Alternatively, an objective reasonably homogenous comparison may be made between contact sport athletes with concussions and those without concussions. As previously noted, using these comparisons, Schatz et al. (2006) reported sensitivity and specificity rates without giving specific cut scores; the criteria for group assignments were not well-defined. Additionally, inclusion of multi-concussed athletes in the concussion group increases the likelihood that significant results will be found when compared to athletes with no neurological history. Further, the available norms are limited to student athletes from high school (ages 13-18) and college aged students (ImPACT Applications Inc., 2013).

Finally, much of the current ImPACT research fails to include comparisons to measures purported to assess the same underling constructs. Some research compares a subset of ImPACT domains to other tests, such as Iverson et al.'s (2005) comparison between ImPACT Reaction Time and the SDMT. While the tests appeared to be measuring the same construct, discriminant validity was not thoroughly examined. Few published studies examine each ImPACT domain comparing composite scores to standardized neuropsychological tests assessing comparable constructs, and at the time of writing no published studies have addressed ImPACT construct and discriminant validity in this manner using an adolescent population.

Rationalization of Current Study

The current study aimed to analyze ImPACT's convergent, discriminant, and diagnostic validity by comparing post-concussion scores from adolescent athletes to those from healthy control athletes. Diagnostic analyses were strengthened by using convergent neuropsychological measures to validate ImPACT composite scores and through the inclusion of a matched healthy control group. Additionally, stringent exclusion criteria were upheld including rejecting subjects with pre-existing psychological diagnoses and cognitive difficulties (i.e., learning disabilities, history of special education, etc.). This requirement aimed to rule out potential confounds that may have affected cognitive scores in other validation studies. It was hypothesized that ImPACT's various domains would demonstrate adequate convergent and discriminant validity. However, it was also hypothesized that ImPACT's diagnostic validity would differ from that of paper-and-pencil measures.

CHAPTER 3: METHODOLOGY

Participants

The present sample of athletes included those ages 12 to 16. Athletes were drawn from two groups: a sports concussion group (SPORT) and a healthy control group (CONT). The SPORT group consisted of 29 athletes ages 12 to 16 who had been referred for neuropsychological assessment following a sports concussion. CONT included 25 healthy athletes aged 12 to 16 who were concussion-free within the previous year and screened for confounding conditions. Details of each group are provided below.

Procedure

Recruitment and Screening: Sports Concussion Group (SPORT)

SPORT participants had been diagnosed with a sports-related concussion by physicians specializing in sports medicine and/or trauma and referred for neurocognitive testing evaluations secondary to ongoing concussion symptoms. Initial concussion diagnoses were determined by the presence of traumatically induced alterations in mental status (with or without loss of consciousness) and/or physiological disruption in brain functioning, as evidence by memory loss, cognitive or mental status alterations, or focal neurological deficits (Kelly et al., 1991). Additional symptoms suggesting concussion included confusion, delayed response, emotional changes, pain, dizziness, visual disturbances, amnesia, and increased intracranial pressure.

Archived referrals for SPORT had been tested at the Kentucky Neuroscience Institute (KNI) at the University of Kentucky Hospital during the time span of October, 2010 through October, 2012. Assessments included a standardized clinical interview with a licensed neuropsychologist and administration of a neuropsychological battery by a licensed psychometrist or by a clinical psychology doctoral student under the supervision of the neuropsychologist. Participants with self-reported or parent-reported psychiatric or psychological disorders diagnosed by a mental health provider (such as depression, anxiety, ADHD, etc.) prior to the concussion were excluded from the present study. Additionally, participants with a self-reported or parent-reported history of learning disabilities, individualized education plans, and/or special education were also excluded. Presence of premorbid mental health diagnoses and history of learning disabilities was determined through record review when available and confirmed through interview prompts, including standardized questions for assessing developmental and learning history. Psychological and learning disability diagnoses were extracted from the neuropsychological report, as diagnoses had been initially documented in the clinical interview portion of the assessments. SPORT athletes were selected from a larger pool of 200+ concussed athletes, resulting in the selection of 46 individuals who met inclusion criteria. Subsequently 17 participants were excluded due to missing data from one or more cognitive tests, resulting in a final SPORT sample size of 29. The excluded participants were not entered into the final dataset and were not available for demographic comparison to the final sample.

Recruitment and Screening: Control Group (CONT)

CONT athletes were recruited from community sports teams, schools, and through flyers hung at gyms, clubs, medical offices, and other agencies where athletes seek services or through email distribution to various sports teams, sports organizations, public schools, and private schools. Parents or guardians of interested participants contacted the first author by either telephone or email. CONT participants were selected to match SPORT demographic characteristics including age, sex, and race as closely as possible. During a telephone screening phase, parents were informed of their child's rights as study participants and verbally consented to provide their child's demographic information and specific medical history. Parents were asked questions about their child's age, sex, year in school, and grades in school along with questions pertaining to psychiatric diagnoses, history of concussion, and history of special education. Based on this interview, participants with self-reported or parent-reported history of concussion in the past year or other neurological disorders and participants with psychiatric or psychological diagnoses (such as depression, anxiety, ADHD, etc.) were excluded as were those with a history of learning disabilities, individualized education plans, and/or special education. Those who met inclusion criteria for the study were invited for a two to three hour evaluation at the University of Kentucky's Department of Psychology.

On-site CONT Evaluations

Evaluations were performed on an individual basis at the University of Kentucky's Department of Psychology. During the evaluation, the participants and their parents provided demographic information and answered questions pertaining to the adolescent's academic, neurologic, and psychiatric history. Next, participants were asked about their history of sports involvement, such as length of participation, level of participation, and types of sports participation. Interviews were conducted by graduate students in a doctoral clinical psychology program. Following the initial paperwork, participants underwent the same clinical assessment battery used for SPORT. Next, the parent or guardian was asked to provide permission to send test results to the home if requested and to fill out a W-9 and authorization for payment form in order to receive $40 compensation for participating.

Materials: Assessment Battery

Paper-and-pencil neuropsychological tests were previously selected as part of a clinical battery. However, the included measures demonstrate evidence for assessing cognitive domains tapped by ImPACT. The measures utilized in this study are comparable to those used in both research and clinical settings to assess cognitive symptoms post-concussion. According to Grindel, Lovell, and Collins (2001), an appropriate adult clinical neuropsychological testing battery typically assesses the following domains: visual memory, verbal memory, attention/concentration, language fluency, motor coordination/psychomotor speed, visuospatial construction, and executive functions/mental flexibility. Maroon et al. (2000) documented a similar adult testing battery used for both clinical and research purposes, with additional support for the use of a verbal memory measure with short delay and long delay free recall and recognition aspects, executive functioning/mental flexibility tasks, language fluency tests, and processing speed/ attention tests. Clinical recommendations for pediatric neuropsychological batteries for the assessment of concussion are less clearly delineated. Additionally, the majority of studies evaluating ImPACT have assessed high school and collegiate level athletes. To date, research has offered limited recommendations for a youth concussion battery and in comparison to adult literature, a paucity of empirically derived assessments exists for determination of convergent validity. As such, the current study compares ImPACT domains to a clinically selected battery that closely adhered to Grindel et al.’s (2001) layout of an appropriate selection for neuropsychological assessment. Some limitations exist given the post-hoc analyses when utilizing a pre-existing clinical battery to assess validity; the current study will attempt to examine each tool given the available validity literature and how the assessment performed in a research setting. Table 1 compares specific assessment measure examples from Grindel et al. (2001), Maroon et al. (2000), and the current study. The current study's assessment measures are described at length below and were administered to both SPORT and CONT. Table 2 shows a full list of the current study's assessment measures categorized as either convergent validity or discriminant validity measures as appropriate for comparisons to ImPACT domains.

Wide Range Achievement Test- Fourth Edition (WRAT4) Reading Subtest

The WRAT4 Reading subtest (Wilkinson & Robertson, 2006) measures basic academic skills and is used as a rapid estimate of literacy. It was standardized on a national sample of over 3,000 individuals ranging in age from 5 to 94. The normative sample was selected according to a national sampling procedure and was stratified by age, gender, ethnicity, geographic region, and parental or participant-obtained education. WRAT4 Reading measures letter and word decoding through letter identification and word recognition. The WRAT4 Reading subtest has been shown to be robust and suitable for use in a brain injury population (Orme et al., 2004).

The WRAT4 Reading subtest is also frequently used as an estimate of premorbid intelligence when baseline or premorbid data are unavailable. The ability to read irregular words is moderately to strongly correlated with intelligence and as a result, word-reading measures have gained widespread use as estimates of pre-injury intelligence (Johnstone et al., 1996; Proto et al., 2012). Generally, reading tests are minimally affected by

Table 1
Comparison of Example Concussion Batteries to Current Neuropsychological Screening Battery

Domain	**Grindel et al. (2001) Measures**	**Maroon et al. (2000) Measures**	**Current Study Measures**
Verbal Memory	CVLT-II	HVLT-R	ImPACT Verbal Memory
	WMS-III LM		CMS Stories Immediate
			CMS Stories Delay
			CMS Stories Recognition
Visual Memory	BVMT-R		ImPACT Visual Memory
			CMS Dots Learning
			CMS Dots Total
			CMS Dots Delay
Processing Speed/ Attention	CPT	TMT A	ImPACT Visual Motor Speed
	SDMT	SDMT	ImPACT Reaction Time
	TMT A	WAIS-IV Digit Span	TMT A
	WAIS-IV Digit Span		
Executive Functions	TMT B	TMT B	TMT B
	WCST	Stroop	D-KEFS Design Fluency
Expressive Language	FAS	FAS	FAS
	Animals	Animals	Animals
Visuospatial Construction	Figure Detection		Beery VMI

Note. CVLT-II = California Verbal Learning Test- 2nd Edition; HVLT-R = Hopkins Verbal Learning Test- Revised; WMS- III LM = Wechsler Memory Scale- 3rd Edition Logical Memory Subtest; CMS = Children's Memory Scale; BVMT-R = Brief Visuospatial Memory Test- Revised; CPT = Continuous Performance Test; TMT = Trails Making Test; SDMT = Symbol Digits Modalities Test; WAIS-IV = Wechsler Adult Intelligence Scales- 4th Edition; WCST = Wisconsin Card Sorting Test; D-KEFS = Delis-Kaplan Executive Function System; VMI = Visual-Motor Integration.

Table 2
Categorization of Measures into Convergent and Discriminant Validity Criterion Variables for Comparison to ImPACT Domains

ImPACT Domain	Convergent Validity	Discriminant Validity
ImPACT Verbal Memory	CMS Stories Immediate	TMT B
	CMS Stories Delay	D-KEFS Design Fluency
	CMS Stories Recognition	Beery VMI
		FAS
		Animals
ImPACT Visual Memory	CMS Dots Learning	TMT B
	CMS Dots Total	D-KEFS Design Fluency
	CMS Dots Delay	Beery VMI
		FAS
		Animals
ImPACT Visual Motor Speed	TMT A	D-KEFS Design Fluency
		Beery VMI
		FAS
		Animals
ImPACT Reaction Time	TMT A	D-KEFS Design Fluency
		Beery VMI
		FAS
		Animals

Note. CMS = Children's Memory Scale; TMT = Trails Making Test; D-KEFS = Delis-Kaplan Executive Function System; VMI = Visual-Motor Integration.

traumatic brain injury (Greene et al., 2008). The WRAT4 Reading subtest has been found to be an acceptable estimate of intellectual intelligence based on its correlation with the WAIS-III Full Scale IQ and Verbal IQ ($r = .64$; Proto et al., 2012). Clinically, WRAT4 Reading scores and other estimates of predicted deviation IQ scores are used to determine whether post-injury IQ is consistent with baseline estimates with differences of greater than two standard deviations generally raising concern about decline in functioning. Optimal use of premorbid estimates of intelligence such as the WRAT4 consists of comparison of one individual's pre-morbid score to that same individual's post-injury estimated intelligence score or post-injury obtained IQ score (Greene et al., 2008). While the WRAT4 Reading subtest is carried over from the WRAT3 Reading subtest, critics have noted that the WRAT4 Reading subtest is limited in terms of extensive validity research given the augmentation and novelty of words on this revised edition; further research is necessary to confirm high WRAT4 Reading subtest correlation with predicted IQ scores (Mullen & Fouty, 2014).

Immediate Post-Concussion Assessment and Cognitive Testing 3.0 (ImPACT)

All participants were administered ImPACT on a lap-top computer. As previously noted, ImPACT is a computerized neuropsychological testing battery consisting of 6 modules: Word Memory, Design Memory, X's and O's, Symbol Matching, Color Match, and Three Letter Memory (Iverson, Lovell, & Collins, 2003). The various combinations of scores are used to assess several cognitive domains including verbal memory, visual memory, attention, reaction time, and response variability. Administration time is approximately 20 minutes and the test can be used with individuals ages 10 to 59. ImPACT's reliability is moderate to high, with internal consistency alphas ranging from

.75-.94 and mean test-retest reliability of .80 over 2 days. See earlier sections for more detail on ImPACT.

Children's Memory Scale (CMS), Dots and Stories Subtests

The CMS (Cohen, 1997) is a comprehensive learning and memory test for children ages 5 to 16. The Dots subtest measures short-delay and long-delay visual memory while the Stories subtest measures short-delay and long-delay verbal memory. Administration of the two subtests takes approximately 15-20 minutes, not including a 30 minute delay between short-delay and long-delay components. CMS has been shown to be reliable and valid in assessing verbal and visual memory deficits following TBI, with an average internal consistency reliability coefficient of .91, a mean test-retest reliability coefficient of .89, and an average inter-rater reliability coefficient of .94 (Pearson Assessment, 2012). CMS demonstrates good reliability over time with high inter-rater reliability based on intra-class correlation (Cohen, 1997). As addressed by Kibby and Cohen (2008), concurrent validity of the CMS is good; the CMS has been shown to correlate well with various other measures of cognitive and intellectual ability, demonstrating at least a moderate relationship between the CMS subtests and other memory measures. When the CMS was compared to the Wechsler Memory Scale- Third Edition, corresponding indexes were found to have moderate to strong correlations (Wechsler, 1997). Additionally, when corresponding CMS and CVLT-C indexes are compared they are moderately to strongly correlated (Cohen, 1997). CMS has also demonstrated adequate convergent validity, is comparable to memory assessment in both WISC-III and WPPSI-R and has good differential sensitivity to detection of memory problems in children with neurodevelopmental disorders (Cohen, 1997). In examining individual subtests, CMS Stories Immediate was predicted by WISC-IV Verbal Comprehension (VCI) Index scores in children with learning disabilities (Kibby & Cohen, 2008), demonstrating a concurrent relationship between verbal knowledge and verbal memory. CMS Dots Locations Learning and Dot Locations Short Delay were sensitive to differences between children with reading disabilities and ADHD (Kibby & Cohen, 2008).

In the present study, CMS Dots was used as the convergent validity measure for ImPACT Visual Memory. ImPACT Visual Memory scores are calculated based on performances from the Design Memory module and the X's and O's module. The Design Memory module consists of 12 target designs presented sequentially twice. A recognition discrimination task immediately assesses recognition of the target designs through presentation of 24 visual designs with the 12 target designs imbedded. A similar recognition discrimination task is presented after a delay. In the X's and O's module, users attempt to remember three screens with X and O patterns in which target stimuli are illuminated in yellow. Following a distraction task in which the user is asked to differentiate between blue squares and red circles, the user is asked to identify the previously illuminated target stimuli from the three X and O screens. Similarly, CMS Dots consists of the presentation of a grid with blue circles three times. Following each presentation, examinees are asked to copy the blue grid design using chips. An immediate interference task consisting of a grid with red circles is completed, followed by immediate free recall of the blue chip grid. After a delay, free recall of the blue chip design measures visual memory retention. Given CMS Dot's convergence with other visual memory measures and the similarity of the visual stimuli presented sequentially for learning in each task, inclusion of an interference task, and inclusion of assessment of visual material after a delay, CMS Dots was deemed an adequate comparison to ImPACT Visual Memory.

CMS Stories was used as the convergent validity measure for ImPACT Verbal Memory. ImPACT Verbal Memory scores are calculated based on performances from the Word Discrimination module which consists of 12 target words presented in list form twice. A recognition discrimination task immediately follows, consisting of 24 semantically similar words with the 12 target words imbedded. After an approximately 20 minute delay, the examinee is presented with a delayed recognition discrimination task utilizing 12 new words imbedded in the 12 target word list. CMS Stories consists of the presentation of two brief stories; following each presentation the examinee repeats elements of the story retained including key words and phrases. Scores are based on retention of specific words described in context. Following a delay, a free recall task evaluates delayed retention for each story. Next, a recognition discrimination task is presented with examinees determining “yes” or “no” whether presented sentences reflect information from the stories by identifying, or discriminating, between key words and semantically similar words or phrases. Given the predominant recognition discrimination component of ImPACT Verbal Memory, the best CMS Stories subcomponent criterion likely is the Stories Recognition portion. As ImPACT Verbal Memory fails to assess any free recall components, the comparison between subtests is that of recognition only.

Trails Making Test Parts A and B (TMT A, TMT B)

The TMT was originally used in the Army Individual Test Battery (1944) and later incorporated into the Halstead-Reitan Battery (Retain & Wolfson, 1985). It assesses and provides information on visual search, visual scanning, processing speed, and mental flexibility (Tombaugh, 2004). Adult TMT can be used with children ages 15 and up, while Children's TMT is adapted from the original version and shortened for use with children ages 5 through 14. TMT A requires individuals to connect circled numbers consecutively as quickly as possible without making mistakes. TMT B adds cognitive complexity as a switching task that requires individuals to alternate between connecting circled numbers and letters consecutively and is thought to include an executive component. Several studies have established TMT validity and sensitivity to brain damage, and it has been deemed suitable to assess for processing speed and motor functioning in traumatic brain injury samples (e.g., Allen, Haderlie, Kazakov, & Mayfield, 2009; Periáñez et al., 2007; Reitan, 1955, 1958, 1971; Reitan & Wolfson, 2004).

TMT A was used as a convergent validity measure for ImPACT Visual Motor Speed and, to a lesser extent, for ImPACT Reaction Time. ImPACT Visual Motor Speed is calculated as an average from X's and O's (described previously) and Three Letters. Three Letters consists of a "distractor task" in which the examinee selects numbers on a grid in descending order as quickly as possible. Following each presentation of the distractor task, three letters are presented. The examinee is asked to remember the letters after each randomized number grid. ImPACT Reaction Time consists of an average from X's and O's (described previously), Symbol Match, and Color Match. Symbol Match consists of a speeded task in which the examinee matches common symbols with the associated number from one through nine. Correct performances are indicated through green matches while incorrect performances are indicated through red matches. Color

Match measures response inhibition and consists of clicking on red, blue, or green buttons presented on the screen followed by presentation of a word either in the same colored ink as the previously presented word or in a different colored ink. The examinee is asked to select the word in the same-colored ink as the initial presentation. TMT A is most similar to the Three Letters task in measuring basic processing speed and is expected to show moderate to large correlations with ImPACT Visual Motor Speed.

TMT B was used to establish discriminant validity for ImPACT Verbal Memory and Visual Memory. While there may be convergence of a modest size with ImPACT Reaction Time given the response inhibition inclusion from the Color Match module and the component of psychomotor speed in TMT B, ImPACT does not purport to measure an executive function domain and thus should not demonstrate high correlations with executive functioning measures.

Delis-Kaplan Executive Function System (D-KEFS), Design Fluency Subtest

The D-KEFS (Delis, Kaplan, & Kramer, 2001) design fluency subtest is intended to assess executive functions such as fluency in developing visual patterns, problem solving, switching, and the ability to inhibit previously drawn responses. The subtest consists of three trials, each lasting 60 seconds. The first two trials involve drawing different figures as quickly as possible using four straight lines to connect dots. The second trial involves the same instructions, but requires the examinee to connect only specific dots in boxes filled with empty and filled dots. The final trial requires the examinee to continue connecting dots, but to switch each time from an empty dot to a filled dot. The D-KEFS system has been shown to be reliable and valid in detecting executive dysfunction in neurological populations (see Delis et al., 2004). In the current study, D-KEFS Design Fluency was used to establish discriminant validity for ImPACT Verbal Memory, Visual Memory, Visual Motor Speed, and Reaction Time. While there may be convergence with TMT B given the executive nature of the task, there is not likely to be strong correlations with ImPACT measures as there is not a specified ImPACT executive functioning domain.

Beery-Buktenica Developmental Test of Visual-Motor Integration- Sixth Edition (Beery VMI)

The Beery VMI (Beery, Beery, & Buktenica, 2010) is a measure of visual motor integration designed for use with children ages 2 through 18. The Beery VMI requires the use of visual discrimination and spatial abilities, along with fine motor skills and visual motor integration. The Beery VMI was standardized on a national sample of 1,737 children and requires test takers to copy figures that increase in complexity. Research indicates that the Beery VMI is appropriate for use in detecting visual perceptual and fine motor difficulties in children with learning disabilities (Aylward, & Schmidt, 1986; Williams et al., 1993). As reviewed by Eddy, Rizzo, and Cavanna (2009), Beery VMI has also shown sensitivity to visuomotor deficits in children with Tourette syndrome and possibly in children with attention deficit hyperactivity disorder. Beery VMI was used to establish discriminant validity for ImPACT Verbal Memory, Visual Memory, Visual Motor Speed, and Reaction Time. While there may be convergence of a small to moderate size with ImPACT Visual Memory given the use of visual stimuli, ImPACT domains does not purport to measure a visuospatial construction.

Verbal Fluency: FAS Phonemic Fluency and Animals Semantic Fluency

Measures of phonemic fluency assess ability to generate words that begin with a specific letter (i.e., F, A, and S; Benton, 1968; Miller, 1984), while measures of semantic fluency assess the individual's ability to generate words from a specific semantic category (i.e., animals). Verbal fluency measures have demonstrated sensitivity to frontal lobe, temporal lobe, and caudate nucleus damage in many disorders including Alzheimer's disease, Huntington's disease, and traumatic brain injury (Tombaugh, Kozak, & Rees, 1999). Research has compared various forms of phonemic fluency (i.e., FAS vs. other letters) and semantic fluency tasks, demonstrating strong evidence of comparability between letters, forms, and categories with FAS demonstrating somewhat higher test-rest correlations (r = .82) than similar short-form phonemic fluency measures (Harrison, Buxton, Husain, & Wise, 2000). The Animals semantic fluency task also demonstrated adequate test-retest reliability. FAS and Animals were used to establish discriminant validity for ImPACT Visual Memory, Visual Motor Speed, and Reaction Time as these domains do not purport to measure expressive language.

Beck Youth Inventory- Second Edition (BYI-II)

The BYI-II (Beck, Beck, & Jolly, 2005) assesses emotional and social functioning in children and adolescents ages 7 to 18. The measure consists of 5 inventories with 20 questions each addressing the areas of depression, anxiety, anger, disruptive behavior, and self-concept. The BYI-II normative sample consists of 1,000 children and adolescents ages 7 to 18 and is representative of the 1999 US Census for age, gender, ethnicity, and social economic status. Test-retest reliability ranges from .74-.93 over a seven to eight day period. Adequate convergent validity has been demonstrated between BYI-II and the Children's Depression Inventory (Beck, Beck, & Jolly, 2005). BYI-II was administered to measure mood and behavioral disruptions that may be related to post-concussion symptoms.

CHAPTER 4: RESULTS

Achieved Power

Due to smaller than expected sample sizes, achieved power was computed to determine the likelihood of detecting significant group differences. Post hoc achieved power analyses for difference between two independent means demonstrated appropriate power analyses for each of the ImPACT domains. Given a calculated effect size of d = 1.03 at $p < 0.05$, Verbal Memory demonstrated achieved power of 0.98. Given a calculated effect size of d = 1.08 at $p < 0.05$, Visual Memory demonstrated achieved power of 0.99. Given a calculated effect size of d = 1.12 at $p < 0.05$, Visual Motor Speed demonstrated achieved power of 0.99. Given a calculated effect size of d = 1.31 at $p < 0.05$, Reaction Time demonstrated achieved power of 0.99.

Demographic Characteristics

As previously noted, participants for SPORT were identified from archival clinical neuropsychological evaluations at KNI. Over 200 neuropsychological files with various diagnoses were gathered for review, with 65 participants entered into a master concussion database. While the master database contains information from re-evaluations (i.e., testing at time 2 or time 3), only initial evaluations were used for the purpose of this study. Initial evaluations were deemed the best representative of initial cognitive deficits following concussion. The master concussion database consisted of individuals who had been diagnosed with concussion and had been tested with ImPACT software. Of those in the database, 42 participants met the age requirements (ages 12 to 16) for inclusion in this study and were further screened for inclusion based on the use of the aforementioned testing battery. Of those 42 participants, 4 were excluded due to non-sport concussion (i.e., concussion secondary to motor vehicle crash). Next, two participants were excluded for history of ADHD, four participants were excluded due to academic difficulties (repeated a grade in school), six participants were excluded due to missing ImPACT scores, eight participants were excluded due to lack of CMS scores, one participant was excluded due to history of a neurological diagnosis, and two participants were excluded due to positive neuroimaging findings. This resulted in a final SPORT sample size of 29. Refer to Figure 1 for a flowchart of SPORT participant recruitment.

Participants for CONT were self-selected through flyers (see previous description) and word-of-mouth from other participants. Thirty individuals were screened for CONT, with 29 of those participants invited to participate in full evaluations. One participant was excluded prior to completing a full telephone screening because English was not the primary language. Following the telephone screener, the parent of two sibling participants did not respond to email and phone call prompts for evaluation scheduling. Two additional participants no-showed or cancelled their evaluation appointments and were unable to reschedule due to time constraints. This resulted in a final CONT sample size of 25. Refer to Figure 2 for a flowchart of CONT participant recruitment.

The final sample of 54 participants consisted of 29 clinical concussion patients and 25 healthy control athletes (see Table 3). The overall sample was 75.9% male with a mean age of 14.26 (*SD* = 1.32) and a mean education of 8.02 years completed (*SD* = 1.434). The racial/ethnic makeup of the sample was 100% Caucasian, as the CONT group was matched for race to archival individuals in the SPORT group. Additionally, 90.7% of the sample was right handed; see Table 3 for additional handedness information. Overall, the majority (70.4%) of participants had no prior history of head

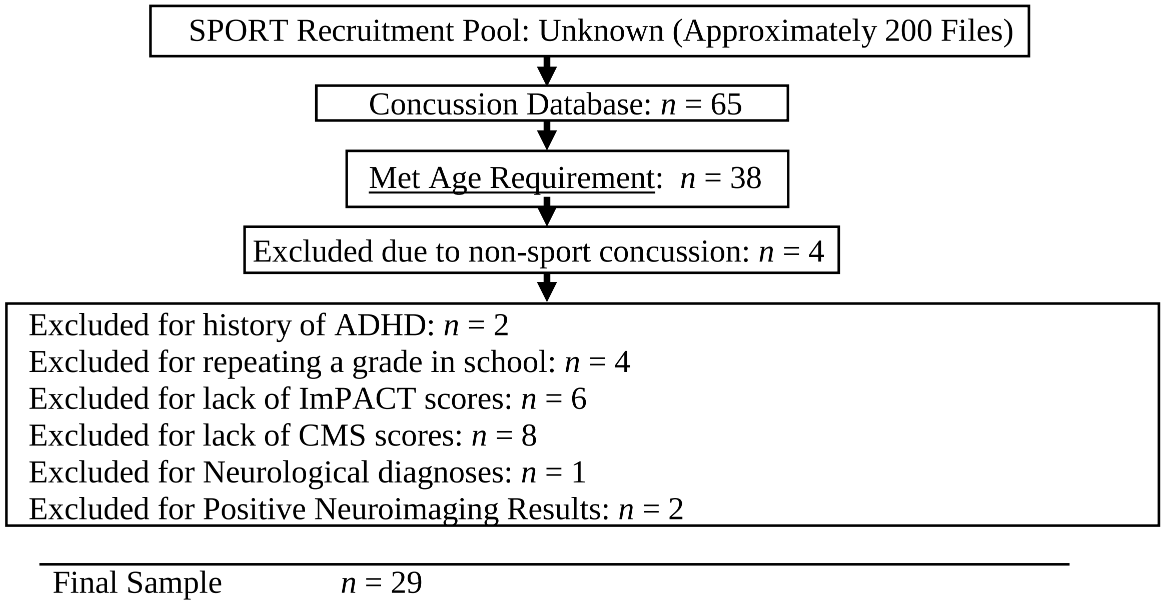

Figure 1. Flow diagram of SPORT participants from initial recruitment to final sample.

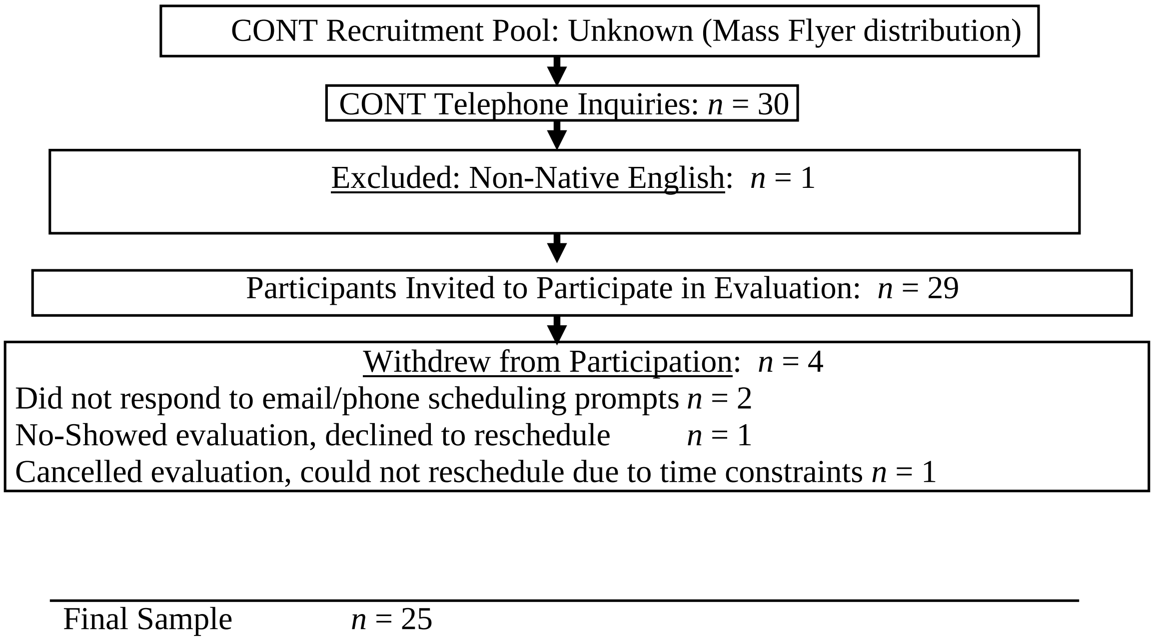

Figure 2. Flow diagram of CONT participants from initial recruitment to final sample.

Table 3
Total Sample Characteristics

		Total Sample N = 54
Male	%	75.9
Age	M	14.26
	SD	1.32
Edu. (yrs. completed)	M	8.02
	SD	1.43
Handedness		
Right	%	96.00
Left Familial	%	4.00
Left Non-Familial	%	0.00
Ambidextrous	%	0.00
WRAT-4 Reading T	M	62.04
	SD	11.33
Ethnicity (Matched)		
Caucasian	%	100
Current Sport		
Football	%	8.00
Soccer	%	44.00
Lacrosse	%	8.00
Basketball	%	12.00
Baseball	%	16.00
Other	%	12.00
Previous Concussions		
0	%	70.4
1	%	16.7
2	%	5.6
3+	%	1.9

Note. Edu. = Education; yrs. = years.

injury. Of those who had experienced previous concussions, 16.7% of participants had experienced one concussion in their lifetimes, 5.6% had experienced two concussions, and 1.9% had experienced three or more concussions.

Parametric analyses were used to explore possible group differences in respect to demographic variables. Refer to Table 4 for demographic characteristics and analyses of significant group differences. Age, sex, education, and handedness exhibited some skewness and kurtosis. Additional nonparametric analyses using the Kruskal-Wallis test were used to compare the groups; there were no significant group differences on these additional analyses for age ($\chi^2 = 0.806$; $p = 0.369$), sex ($\chi^2 = 0.385$; $p = 0.535$), education ($\chi^2 = 0.400$; $p = 0.527$), or handedness ($\chi^2 = 1.458$; $p = 0.227$). Significant differences were found between groups in the areas of current sport at time of evaluation ($\chi^2 = 22.16$; $p = 0.00$) and history of previous concussions ($\chi^2 = 4.15$.; $p = .042$). The majority of individuals in SPORT were assessed while participating in football, while the majority of individuals in CONT were assessed while participating in soccer. While this difference may limit generalizability, it may also be reflective of multi-sport athletes assessed at varying times throughout the year (i.e., football players were assessed in the fall and soccer players were assessed in the late spring/summer). Additionally, when overall history of prior concussions was examined, significant differences were found between groups ($\chi^2 = 4.15$; $p = 0.04$), with 84% of CONT participants who were concussion-free compared to 69% of SPORT participants who were concussion-free prior to the index concussion. Further, 12% of CONT and 20.7% of SPORT had experienced one prior concussion, 4% of CONT and 6.9% of SPORT had experienced two prior concussions, and an additional 3.4% of SPORT had experienced four prior concussions. A significant

Table 4
Demographic Group Differences

		Group Characteristics		Comparisons	
		CONT	**SPORT**	*N* = 54	
		n = 25	*n* = 29	*F*, χ^2	*p*
Male	%	72.00	79.30	0.39 (χ^2)	0.53
Age	*M*	14.08	14.41	0.86 (*F*)	0.36
	SD	1.32	1.32		
Edu. (yrs completed)	*M*	7.92	8.10	0.22 (*F*)	0.64
	SD	1.41	1.47		
Handedness				2.74 (χ^2)	0.43
Right	%	96.00	86.20		
Left Familial	%	4.00	6.90		
Left Non-Familial	%	0.00	3.40		
Ambidextrous	%	0.00	3.40		
WRAT4 Reading T	*M*	62.04	50.83	18.86 (*F*)	0.00**
	SD	11.33	7.50		
Ethnicity (Matched)				--	--
Caucasian	%	100	100		
Current Sport				22.16 (χ^2)	0.00**
Football	%	8.00	65.50		
Soccer	%	44.00	6.90		
Lacrosse	%	8.00	0.00		
Basketball	%	12.00	10.30		
Baseball	%	16.00	0.00		
Other	%	12.00	6.90		
Previous Concussions				4.15 (χ^2)	0.04*
0	%	84.00	69.00		
1	%	12.00	20.70		
2	%	4.00	6.90		
3	%	0.00	0.00		
4	%	0.00	3.40		

Note. SPORT = Sports Concussion; CONT = Healthy Control; Current Sport = current or most recent sport season at time of evaluation; Edu. = education; yrs = years; WRAT-4 = Wide Range Achievement Test- Fourth Edition; T = T-score (*M* = 50, *SD* = 10)
$^*p < .05$, $^{**}p < .01$

difference in history of concussion is consistent with recruitment efforts to exclude CONT participants with a history of concussion within the previous year. WRAT-4 Reading was used as an estimate of premorbid intelligence to determine baseline differences between CONT and SPORT. The total sample's average WRAT-4 Reading T-score was 56.02 (*SD* = 10.94). There were significant differences in Reading subtest scores between groups with CONT demonstrating a significantly higher mean T-score (*M* = 62.04, *SD* = 11.33) than SPORT (*M* = 50.83, *SD* = 7.50). Kurtosis analyses indicated that CONT's WRAT-4 distribution was slightly platykurtic, or flat (-1.15 with normal range between -1.0 and 1.0). Three CONT outliers (WRAT-4 T-scores = 80) were identified; even when these outliers were removed, there continued to be significant differences between groups. While the difference in WRAT-4 Reading scores is a limitation that indicates the possibility of unequal comparison groups and limits generalizability, other potential explanations are addressed in the discussion section.

Table 5 presents symptoms and concussion severity indicators for SPORT, including self-reported post-concussion physical, cognitive, and mood symptoms. All SPORT participants met criteria for mTBI and were diagnosed with concussion by a physician. SPORT participants were evaluated an average of 53.79 days (*SD* = 48.37; range 4-112) post-concussion. While this range demonstrates wide variability between times assessed post-concussion, each of the SPORT participants was deemed symptomatic by the referring physician. This sample is a post-concussion group with symptom duration longer than the average recovery period of 1.5 to 2 weeks. While 17.5% of the sample lost consciousness for an unknown length of time under 30 minutes, the majority of participants (55.2%) did not experience any loss of consciousness.

Table 5

SPORT Self-Reported Physical, Cognitive, and Mood Symptoms

Concussion Group Characteristics *n* = 29					
Days Post-concussion*	*M*	53.79	**Cognitive Difficulties**		
	SD	48.37	Attention	%	62.10
LOC			STM	%	51.70
No LOC	%	55.20	LTM	%	0.00
LOC < 1 min.	%	10.30	Processing Speed	%	55.20
LOC 1-5 min.	%	6.80	Expressive Language	%	20.70
LOC 6-10 min.	%	3.40	Receptive Language	%	0.00
LOC 11-15 min.	%	3.40	EF	%	6.90
LOC 16-20 min.	%	3.40	Visuospatial	%	6.90
Unknown length (< 30 min.)	%	17.50	**Physical Symptoms**		
Retrograde Amnesia			Fatigue	%	48.30
None	%	62.00	Sleep Problems	%	44.80
< 5 min.	%	6.80	Headache	%	62.10
< 60 min.	%	10.30	HA/Resolved	%	20.70
1-3 hours	%	10.30	Vertigo/ Dizziness	%	55.20
1 day	%	3.40	Vision Changes	%	34.50
Unknown	%	7.20	Hearing Changes	%	0.00
Event Amnesia	%	55.20	Smelling Changes	%	3.40
Anterograde Amnesia			Taste Changes	%	0.00
None	%	55.20	**Mood Symptoms**		
< 5 min.	%	13.60	Aggression	%	55.20
< 60 min.	%	6.80	Anxiety	%	17.20
1-12 hours	%	10.30	Depression	%	17.20
12-24 hours	%	13.70	Labile Emotions	%	20.70
Unknown	%	0.00	Apathy	%	17.20

Note. SPORT = Sports Concussion; LOC = loss of consciousness; min. = minutes; STM = short-term memory; LTM = long-term memory; EF = executive functioning; HA/Eval. = Headache resolved at time of evaluation. * Notes days post-concussion at the time of evaluation, via self-report and estimates from parent/guardian

Additionally, a majority of participants did not experience either retrograde amnesia (62.0%) or anterograde amnesia (55.2%). However, 55.2% of the SPORT group experienced event amnesia due to either alteration of consciousness or loss of consciousness. The most common self-reported cognitive complaint was attention difficulties (62.1%), followed by difficulties in the following cognitive domains: processing speed (55.2%), short-term memory (51.75), expressive language (20.7%), executive functions (6.9%), and visuospatial functions (6.9%). The most common self-reported SPORT physical complaint was headache (62.1%), followed by vertigo/dizziness (55.2%), fatigue (48.3%), sleep problems (44.8%), vision changes (34.5%), and olfactory changes (3.4%). An additional 20.7% of the sample had experienced post-concussion headaches that had resolved prior to evaluation. Finally, a large number of SPORT participants endorsed continued mood symptoms, with 55.2% endorsing aggression, 20.7% endorsing labile emotions, 17.2% endorsing anxiety, 17.2% endorsing depression, and 17.2% endorsing apathy.

Cognitive Test Differences

Table 6 presents ImPACT and neuropsychological test data by group. Significant group differences at $p < 0.01$ were found in each of the four ImPACT domains analyzed: ImPACT Verbal Memory ($F = 13.927$; $p = 0.000$), ImPACT Visual Memory ($F = 15.593$; $p = 0.000$), ImPACT Visuomotor Speed ($F = 16.684$; $p = 0.000$), and ImPACT Reaction Time ($F = 17.026$, $p = 0.000$). SPORT athletes scored significantly lower than CONT athletes on all of these ImPACT domains. Additional significant group differences were found at $p < 0.01$ on the following paper-and-pencil neuropsychological measures: D-KEFS Design Fluency ($F = 17.026$; $p = 0.000$), TMT B ($F = 12.621$; $p = 0.001$),

Table 6

Mean T Scores and Standard Deviations of Cognitive Measures by Domain with Initial Analysis of Variance Results

	Group						
	CONT		SPORT				
Measure	*M*	*SD*	*M*	*SD*	*F*	*p*	*d*
Verbal Memory							
ImPACT Verbal Memory	55.28	11.610	42.10	13.975	13.927	0.000**	1.03
CMS Stories Immediate	51.80	10.352	48.28	10.173	1.585	0.214	0.34
CMS Stories Delay	51.44	9.938	47.76	10.013	1.827	0.182	0.37
CMS Stories Recognition	51.71	10.469	49.66	11.518	0.453	0.504	0.19
Visual Memory							
ImPACT Visual Memory	56.76	11.552	43.14	13.503	15.593	0.000**	1.08
CMS Dots Learning	53.16	11.037	47.03	10.992	4.154	0.047*	0.56
CMS Dots Total	51.92	11.920	46.79	11.331	2.620	0.112	0.44
CMS Dots Delay	52.12	10.150	44.76	12.132	5.737	0.020*	0.66
Processing Speed							
ImPACT Visual Motor Speed	52.28	11.182	39.69	11.390	16.684	0.000**	1.12
TMT A	54.52	15.974	49.41	10.179	2.017	0.162	0.38
ImPACT Reaction Time	51.68	12.023	38.14	8.344	23.627	0.000**	1.31
Executive Functions							
D-KEFS Design Fluency	61.28	9.629	51.17	8.375	17.026	0.000**	1.12
TMT B	52.80	10.548	41.38	12.740	12.621	0.001**	0.98
Expressive Language							
FAS	48.60	8.679	41.66	8.112	9.224	0.004**	0.83
Animals	57.28	12.212	48.66	10.788	7.595	0.008**	0.75
Visuospatial Construction							
Beery VMI	52.08	3.861	40.07	8.648	41.081	0.000**	1.79

Note. CONT = Healthy athlete control group; SPORT = Sports concussion group; *M* = mean; *SD* = standard deviation; *d* = Cohen's *d* effect size. T-scores standardized unit, mean of 50 and a standardized deviation of 10. * $p < .05$; ** $p < .01$

phonemic fluency (FAS; $F = 9.224$; $p = 0.004$), semantic fluency (Animals; $F = 7.595$; $p = 0.008$), and Beery VMI ($F = 41.081$; $p = 0.000$). SPORT athletes scored significantly lower than CONT athletes on all of these additional measures. Significant group differences were also found at $p < 0.05$ on CMS Dots Learning ($F = 4.154$; $p = 0.047$) and CMS Dots Delay (F = F.737; $p = 0.020$).

Convergent Validity

Skewness and kurtosis values for each test were within the appropriate ranges, suggesting a normal distribution. Pearson correlations were examined by domain to evaluate convergence. Table 7 details Pearson correlations for each of the ImPACT and neuropsychological measures. Table 8 shows correlations between each ImPACT domain and the selected convergent and discriminant validity measures. Convergent validity will be addressed by domains beginning with the correlations between ImPACT domains.

Inter-relationship of ImPACT Composite Scores

Table 7 shows that all of the ImPACT domains demonstrated significant large correlations with each other with the exception of a medium correlation between Visual Memory and Reaction Time ($r = .356$; $p = .008$). These correlations were larger than expected and underscore the potential of a similar underlying construct, overlapping constructs, and/or method variance.

Table 8 shows results from predicted convergent and discriminant validity coefficients between ImPACT domains and selected criterion variables. For the Verbal Memory domain, it can be seen that none of the hypothesized convergent validity coefficients reached statistical significance. In contrast, all three of the discriminant

Table 7

Pearson-r Correlations for ImPACT Composite T- Scores and Neuropsychological Concussion Screening Measures T-Scores

Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
ImPACT Composite															
(1) Verbal Memory	--														
(2) Visual Memory	.660**	--													
(3)Visual Motor Speed	.643**	.568**	--												
(4) Reaction Time	.561**	.356**	.690**	--											
Concussion Battery															
(5) CMS Stories Immed	**.100**	.240	.149	.219	--										
(6) CMS Stories Delay	**.188**	.342**	.168	.218	.936**	--									
(7) CMS Stories Recog	**.168**	.268	.158	.184	.725**	.719**	--								
(8) CMS Dots Learning	.569**	**.474****	.358**	.448	.284*	.317*	.226	--							
(9) CMS Dots Total	.602**	**.478****	.414**	.493**	.280*	.305*	.191	.931**	--						
(10) CMS Dots Delay	.455**	**.383****	.401**	.392**	.341*	.372**	.143	.733**	.802**	--					
(11) TMT A	.158	.221	**.143**	**.174**	.197	.291*	.178	.231	.248	.261	--				
(12) TMT B	*.509***	*.424***	.533**	.542**	.407**	.401**	.379**	.394**	.370**	.257	.489**	--			
(13) D-KEFS DF	*.543***	*.535***	*.636***	*.680***	.233	.292*	.202	.397**	.426**	.431**	.269*	.582**	--		
(14) FAS	.354**	*.309**	*.559***	*.539***	.080	.066	.012	.361**	.327*	.313**	.248	.444**	.557*	--	
(15) Animals	.507**	*.322**	*.519***	*.362***	.160	.184	.267	.157	.222	.241	.153	.277**	.293*	.439**	--
(16) Beery VMI	*.459***	*.586***	*.400***	*.483***	.307*	.319*	.321*	.378**	.327**	.302**	.118	.548**	.457**	.309*	.336*

Note. ImPACT = Immediate Post Concussion Assessment and Cognitive Testing; CMS = Children's Memory Scale; Immed = Immediate; Recog = Recognition; D-KEFS DF = Delis-Kaplan Executive Function System Design Fluency subtest; Beery VMI = Beery Visual-Motor Integration; T-scores are a standardized unit with a mean of 50 and a standardized deviation of 10. Convergent validity correlations appear in **bold** while divergent validity correlations appear in *italics*.

* p < .05

**p < .01

Table 8
Convergent and Discriminant Validity Pearson-r Coefficients for each ImPACT Domain

ImPACT Domain	Convergent Validity	*r*	*p*	Discriminant Validity	*r*	*p*
Verbal Memory	CMS Stories Immed.	.100	.472	TMT B	.509	.000
	CMS Stories Delay	.188	.173	D-KEFS Design Fluency	.543	.000
	CMS Stories Recog.	.168	.229	Beery VMI	.459	.000
	Median Convergent Value	*.168*	--	*Median Discriminant Value*	*.509*	--
Visual Memory	CMS Dots Learning	.474	.000	TMT B	.424	.001
	CMS Dots Total	.478	.000	D-KEFS Design Fluency	.535	.000
	CMS Dots Delay	.383	.004	Beery VMI	.586	.000
				FAS	.309	.023
				Animals	.322	.018
	Median Convergent Value	*.474*	--	*Median Discriminant Value*	*.424*	--
Visual Motor Spd.	TMT A	.143	.301	D-KEFS Design Fluency	.636	.000
				Beery VMI	.400	.003
				FAS	.559	.000
				Animals	.519	.000
				Median Discriminant Value	*.539*	--
Reaction Time	TMT A	.174	.207	D-KEFS Design Fluency	.680	.000
				Beery VMI	.483	.000
				FAS	.539	.000
				Animals	.362	.007
				Median Discriminant Value	*.511*	--

Note. CMS = Children's Memory Scale; Immed. = Immediate; Recog. = Recognition; Spd. = Speed; TMT = Trails Making Test; D-KEFS = Delis-Kaplan Executive Function System; VMI = Visual-Motor Integration.

validity coefficients were statistically significant with a median correlation of .509, an unexpected result.

Turning next to the Visual Memory domain, all convergent validity coefficients were statistically significant with a median correlation of .474. All divergent validity coefficients were also statistically significant with a median value of .424.

The Visual Motor Speed demonstrated a statistically nonsignificant correlation with the convergent validity measure. Once again, all divergent validity coefficients were statistically significant with a median value of .539.

The Reaction Time domain exhibited a similar pattern to the Visual Motor Speed domain, with a statistically nonsignificant convergent validity coefficient. All Reaction Time divergent validity coefficients were statistically significant with a median value of .511.

Discriminant Validity

Discriminant validity was addressed using Maerlender et al.'s (2013) multi-trait mono-method approach described in earlier sections. Maerlender et al.'s (2013) formula (T1 *r* [(T2 + T3 + T4)/3]; T1 = single ImPACT domain T-score; T2, T3, and T4 = other ImPACT domain T-scores) was replicated. However, the formula was modified slightly for inclusion of paper-and-pencil discriminant validity analyses. As such, composite T-scores consisting of the average of domain specific neuropsychological screening battery test scores were correlated with the averaged linear combination of discriminant composites. When operationalizing the neuropsychological screening battery test composite scores, an averaged composite score for tests with multiple components (such as CMS Dots or Stories) was calculated prior to computing correlations (e.g., T1 in the above formula = (T1 + T2 + T3)/3 in which T1 is CMS Stories Immediate T-score, T2 is CMS Stories Delay T-score, and T3 is CMS Stories Recognition T-score). Table 9 details the components of the Maerlender et al. (2013) formulas for each discriminant validity coefficient, and Table 10 details correlations between composite scores and the multiply operationalized discriminant variables.

Discriminant validity analyses demonstrated that all four of the ImPACT domains shared significant method variance with each other with all correlations significant at $p < .01$. The median discriminant validity coefficient was .68. Unexpectedly, discriminant validity analyses of the neuropsychological screening battery showed similar significant shared method variance with all correlations significant at $p < .05$. The median neuropsychological screening battery discriminant validity value was .47.

Diagnostic Validity

Clinicians assessing sports concussion must make individual classification decisions on the basis of several test results within a complete battery. Clinically, a variety of methods may be used to determine cognitive changes post injury. If baseline testing data are available, clinicians may document significant cognitive discrepancies between pre and post testing sessions. This process introduces a level of subjectivity, as clinical acumen may be necessary to determine whether cognitive changes are clinically relevant from a neuropsychological perspective. Thus, diagnostic validity was explored in an attempt to assess clinical significance from a neuropsychological standpoint. Diagnostic validity was analyzed using the cut score method to determine group membership using T-score cut scores. At selected cutting scores, sensitivity and specificity were calculated for each of the ImPACT domains (ImPACT Verbal Memory,

Table 9
Components of the Multiply-operationalized Multi-trait, Mono-method Formulas for each Discriminant Validity Coefficient

	Composite	Discriminant Validity Coefficient
ImPACT		
Verbal Memory	Verbal Memory	Visual Memory, Visual Motor Speed, Reaction Time
Visual Memory	Visual Memory	Verbal Memory, Visual Motor Speed, Reaction Time
Visual Motor/ Processing Speed	Visual Motor Speed	Verbal Memory, Visual Memory, Reaction Time
Reaction Time	Reaction Time	Verbal Memory, Visual Memory, Visual Motor Speed
NP Screening Battery		
Verbal Memory	CMS Stories Immediate, Delayed, Recognition	Visual Memory Composite, TMT A, TMT B, D-KEFS Design Fluency, FAS, Animals, Beery VMI
Visual Memory	CMS Dots Learning, Total, Delay	Verbal Memory Composite, TMT A, TMT B, D-KEFS Design Fluency, FAS, Animals, Beery VMI
Processing Speed	TMT A	Verbal Memory Composite, Visual Memory Composite, TMT B, D-KEFS Design Fluency, FAS, Animals, Beery VMI
Executive Functions 1	TMT B	Verbal Memory Composite, Visual Memory Composite, TMT A, FAS, Animals, Beery VMI
Executive Functions 2	D-KEFS Design Fluency	Verbal Memory Composite, Visual Memory Composite, TMT A, FAS, Animals, Beery VMI
Expressive Language 1	Phonemic Fluency (FAS)	Verbal Memory Composite, Visual Memory Composite, TMT A, TMT B, D-KEFS Design Fluency, Beery VMI
Expressive Language 2	Semantic Fluency (Animals)	Verbal Memory Composite, Visual Memory Composite, TMT A, TMT B, D-KEFS Design Fluency, Beery VMI
Visuospatial Construction	Beery VMI	Verbal Memory Composite, Visual Memory Composite, TMT A, TMT B, D-KEFS Design Fluency, FAS, Animals

Note. NP = neuropsychological.

Table 10
Discriminant Validity: Pearson Correlations (p-values) of Multiply-operationalized ImPACT and NP Composite Scores Using Multi-trait, Mono-method

	ImPACT	NP Screening Battery
Verbal Memory Composite vs. Others	0.74** (0.00)	0.31* (0.03)
Visual Memory Composite vs. Others	0.62 ** (0.00)	0.46** (0.00)
Visual Motor/ Processing Speed Composite vs. Others	0.76 ** (0.00)	0.38* (0.01)
Reaction Time Composite vs. Others	0.61** (0.00)	--
Executive Function 1 Composite vs. Others	--	0.65** (0.00)
Executive Function 2 Composite vs. Others	--	0.59** (0.00)
Expressive Language 1 Composite vs. Others	--	0.48** (0.00)
Expressive Language 2 Composite vs. Others	--	0.36* (0.01)
Visuospatial Construction	--	0.54** (0.00)
Median Value	*0.68*	*0.47*

Note. NP = neuropsychological.
*$p < .05$
**$p < .01$

ImPACT Visual Memory, ImPACT Visual Motor Speed, and ImPACT Reaction Time) and for the traditional paper-and-pencil neuropsychological screening battery (CMS Stories Delay, CMS Dots Delay, TMT A, TMT B, FAS, Animals, and Beery VMI). Categorization as SPORT athletes was used to determine presence of concussion (sensitivity).

Of note, one factor that may affect the sensitivity and specificity analyses is the wide range and variability of time since injury in the SPORT group (*M* = 53.79 days; *SD* = 48.37; range = 4-112 days post-concussion). While it is possible that some of the individuals were within the range of expected typical recovery, SPORT participants were all referred by physicians with follow-up testing occurring quickly after referral (typically 2-5 days). These participants were deemed symptomatic by the referring physician and continued to report symptoms upon neuropsychological interview. As a result, all SPORT participants were deemed to be within the acute, symptomatic post-concussion period and were included in the target sensitivity group for analyses. Previously noted discrepancies between concussion operational definitions contributes to the appropriateness of including all symptomatic individuals in the target group. Despite variability in operational definitions one pronounced similarity is present in each definition, namely the presence of cognitive symptoms is not required for diagnosis. Concussed individuals are far more likely to endorse physical complaints. In the current study, while all SPORT participants were symptomatic not all were experiencing cognitive complaints. Given the potential absence of cognitive symptoms post-concussion, limitations of neurocognitive data are pertinent to address. For instance, it is likely (if not probable) that when testing data are used independently for diagnostic analyses individuals with non-cognitive concussion symptoms are likely to be misclassified as healthy. Such potential for misclassification points to the necessity of analyzing neurocognitive data with additional tools for tracking physical symptoms. This limitation of neurocognitive leads to cautionary interpretations of the diagnostic analyses presented in this study.

Given clinical discrepancies in determining whether non-optimal scores are indicative of clinical impairment following concussion, two cut scores were compared: a T-score of ≤ 36 (qualitative classification of borderline impaired using deviation IQ scores) and a more stringent T-score cutoff of ≤ 29 (qualitative classification of impaired using deviation IQ scores). T-scores above 36 were considered to be within normal limits as they demonstrate qualitatively low average and above functioning, which is within the spectrum of appropriate performance on neuropsychological testing. The T-score cut scores are transformed from deviation IQ scores, with impairment quantified as scores ≥ 1.5 standard deviations below the mean (T-score ≤ 36) or ≥ 2 standard deviations below the mean (T-score ≤ 29).

Table 11 presents sensitivity, specificity, positive predictive power, and negative predictive power for a cut score of ≤ 36 (qualitatively borderline impaired). The assumed base rate of concussions resulting in prolonged symptoms is 50% for the current study, given estimates of a 40 to 60% base rate presented by Garden and Sullivan (2010). At a T-score cutoff of ≤ 36, sensitivity rates for the ImPACT domains ranged from .31 (Visual Motor Speed) to .41 (Verbal Memory) with a median ImPACT domain sensitivity rate of .36. Sensitivity rates for the neuropsychological screening battery measures ranged from .03 (CMS Stories Immediate and CMS Stories Delayed Recall) to .31 (phonemic fluency) with a neuropsychological screening battery median sensitivity rate of .14. Although

Table 11
Sensitivity and Specificity of ImPACT to Persistent Concussion Symptoms at Assumed Base Rate of 50%: Cut Score T ≤ 36

Measure	Sensitivity	Specificity	PPP	NPP
ImPACT Verbal Memory	0.41	1.00	1.00	0.60
ImPACT Visual Memory	0.34	1.00	1.00	0.57
ImPACT Visual Motor Speed	0.31	0.92	0.82	0.53
IMPACT Reaction Time	0.38	0.68	0.79	0.55
Median Value	*0.36*	*0.96*	*0.91*	*0.56*
CMS Stories Immediate	0.03	0.92	0.33	0.45
CMS Stories Delay	0.03	0.96	0.50	0.46
CMS Stories Recognition	0.07	0.96	0.67	0.47
CMS Dots Learning	0.14	0.92	0.67	0.48
CMS Dots Total	0.17	0.88	0.63	0.48
CMS Dots Delay	0.24	0.88	0.70	0.50
Trails A	0.07	0.88	0.40	0.45
Trails B	0.24	0.92	0.78	0.51
D-KEFS Design Fluency	0.07	1.00	1.00	0.48
Phonemic Fluency FAS	0.31	0.92	0.82	0.53
Semantic Fluency Animals	0.14	1.00	1.00	0.50
Beery VMI	0.31	1.00	1.00	0.56
Median Value	*0.14*	*0.92*	*0.69*	*0.48*

Note. PPP = positive predictive power; NPP = negative predictive power; ImPACT = = Immediate Post Concussion Assessment and Cognitive Testing; CMS = Children’s Memory Scale; D-KEFS = Delis-Kaplan Executive Function System; Beery VMI = Beery Visual-Motor Integration; T-scores are a standardized unit with a mean of 50 and a standardized deviation of 10.

sensitivity rates were generally higher for the ImPACT domains than the screening battery, all of the sensitivity rates are modest indicating potential suboptimal accuracy in categorizing individuals diagnosed with concussion at a T-score cutoff of ≤ 36. Specificity rates for the ImPACT domains ranged from .68 (Reaction Time) to 1.00 (Verbal Memory and Visual Memory) with a median rate of .96. All but the Reaction Time domain adequately categorized non-concussed individuals. Specificity rates on the neuropsychology screening battery were all appropriate and ranged from .88 (CMS Dots Total, CMS Dots Delay, and TMT A) to 1.00 (D-KEFS Design Fluency, semantic fluency, and Beery VMI) with a median rate of .92.

Table 12 exhibits sensitivity, specificity, positive predictive power, and negative predictive power rates for a cut score of ≤ 29 (qualitatively impaired). At a more stringent T-score cutoff of ≤ 29, sensitivity rates for the ImPACT domains were all inadequate and ranged from .10 (Reaction Time) to .24 (Visual Memory) with a median ImPACT domain sensitivity rate of .21. Sensitivity rates for the screening battery were also inadequate, ranging from .00 (CMS Stories Delay, CMS Stories Recognition, semantic fluency, and D-KEFS Design Fluency) to .54 (phonemic fluency) with a median sensitivity rate of .05. Specificity rates for the ImPACT domains were high, ranging from .96 (Reaction Time) to 1.00 (Verbal Memory, Visual Memory, and Visual Motor Speed) with a median rate of 1.00. Specificity rates for the screening battery were also high, ranging from .92 (CMS Dots Learning and CMS Dots Total) to 1.00 (CMS Stories Immediate, CMS Stories Delay, CMS Stories Recognition, TMT A, phonemic fluency, semantic fluency, D-KEFS Design Fluency, and Beery VMI) with a median rate of 1.00.

Table 12
Sensitivity and Specificity of Traditional Screening Battery at Assumed Base Rate of 50%: Cut Score T ≤ 29

Measure	Sensitivity	Specificity	PPP	NPP
ImPACT Verbal Memory	0.21	1.00	1.00	0.52
ImPACT Visual Memory	0.24	1.00	1.00	0.53
ImPACT Visual Motor Speed	0.21	1.00	1.00	0.52
IMPACT Reaction Time	0.10	0.96	0.75	0.48
Median Value	*0.21*	*1.00*	*1.00*	*0.52*
CMS Stories Immediate	0.03	1.00	1.00	0.47
CMS Stories Delay	0.00	1.00	--	0.46
CMS Stories Recognition	0.00	1.00	--	0.46
CMS Dots Learning	0.07	0.92	0.50	0.46
CMS Dots Total	0.07	0.92	0.50	0.46
CMS Dots Delay	0.07	0.96	0.67	0.47
Trails A	0.03	1.00	1.00	.047
Trails B	0.21	0.96	0.86	0.51
Phonemic Fluency FAS	0.54	1.00	1.00	0.47
Semantic Fluency Animals	0.00	1.00	--	0.46
D-KEFS Design Fluency	0.00	1.00	--	0.46
Beery VMI	0.10	1.00	1.00	0.49
Median Value	*0.05*	*1.00*	*0.86*	*0.47*

Note. PPP = positive predictive power; NPP = negative predictive power; ImPACT = = Immediate Post Concussion Assessment and Cognitive Testing; CMS = Children's Memory Scale; D-KEFS = Delis-Kaplan Executive Function System; Beery VMI = Beery Visual-Motor Integration; T-scores are a standardized unit with a mean of 50 and a standardized deviation of 10.

Group classification was then determined using the ImPACT battery and the neuropsychological screening battery separately for each cut score, with a T-score of ≤ 36 on any one or more measures used to determine impairment followed by a T-score of ≤ 29 or lower on any one or more measures used to determine impairment. Table 13 presents classification accuracy for the ImPACT domains at both cut scores, Table 14 presents classification accuracy for the neuropsychology screening battery at both cut scores, and Table 15 presents classification accuracy for a combined battery with scores from both ImPACT and the screening battery.

When ImPACT measures alone were examined at a cut score of 36T or lower, 76% of CONT was classified correctly as healthy while 52% of the SPORT group was correctly classified as concussed. At a cut score of 29T or lower, ImPACT measures correctly classified 96% of CONT as healthy while 31% of SPORT was correctly classified as concussed. When the neuropsychological screening battery measures were examined at a cut score of 36T or lower, 68% of CONT was classified correctly as healthy while 79% of SPORT was correctly classified as concussed. At a cut score of 29T or lower, the screening battery correctly classified 88% of CONT as healthy while 34% of SPORT was correctly classified as concussed.

When the ImPACT measures and the screening battery were combined to produce a fuller neuropsychological battery, at a cut score of 36T or lower 64% of SPORT was correctly classified as concussed. At a cut score of 29T, the combined battery correctly classified 88% of CONT as healthy and 48% of SPORT as concussed.

Table 13
Classification of Individuals in Known Groups into Groups Using Cut Scores: ImPACT Domains

	Group Classification Using Cut Score		
Known Group	Healthy Athlete	Concussion	% Correct
	Cut T-Score ≤ 36		
CONT	19	4	76%
SPORT	14	15	52%
	Cut T-Score ≤ 29		
CONT	24	1	96%
SPORT	20	9	31%

Note. CONT = Healthy athlete control group; SPORT = Sports concussion group

Table 14
Classification of Individuals in Known Groups into Groups Using Cut Scores: Neuropsychological Screening Battery

	Group Classification Using Cut Score		
Known Group	Healthy Athlete	Concussion	% Correct
	Cut T-Score ≤ 36		
CONT	17	8	68%
SPORT	6	23	79%
	Cut T-Score ≤ 29		
CONT	22	3	88%
SPORT	19	10	34%

Note. CONT = Healthy athlete control group; SPORT = Sports concussion group

Table 15
Classification of Individuals in Known Groups into Groups Using Cut Scores: Complete Battery (ImPACT and Screening Battery)

	Group Classification Using Cut Score		
Known Group	Healthy Athlete	Concussion	% Correct
	Cut T-Score ≤ 36		
CONT	16	9	64%
SPORT	4	25	86%
	Cut T-Score ≤ 29		
CONT	22	3	88%
SPORT	15	14	48%

Note. CONT = Healthy athlete control group; SPORT = Sports concussion group

Mood Differences

Table 16 presents results from the BYI-II statistically. No significant group differences on objective mood scores (BYI-II) were found in the domains of self-concept, anxiety, depression, anger, or disruptive behavior. However, subjective differences between groups were noted following clinical interview queries. When asked about subjective changes in each domain independently, SPORT athletes reported increased aggression, labile emotions, anxiety, depression, and apathy. CONT participants denied any ongoing mood issues.

Table 16
Mean T Scores and Standard Deviations of BYI-II by Domain with Initial Analysis of Variance Results

	Group						
	CONT		SPORT				
BYI-II Domain	*M*	*SD*	*M*	*SD*	*F*	*p*	*d*
Self-Concept	51.32	7.554	50.48	8.496	0.144	0.706	0.10
Depression	46.40	7.118	46.52	6.770	0.693	0.409	0.02
Anxiety	47.92	9.508	49.93	8.244	0.004	0.951	0.23
Anger	43.64	6.231	46.62	7.043	2.673	0.108	0.44
Disruptive Behavior	43.28	4.486	47.24	9.109	3.904	0.053	0.55

Note. CONT = Healthy athlete control group; SPORT = Sports concussion group; BYI-II = Beck Youth Inventory 2nd Edition; *M* = mean; *SD* = standard deviation; *d* = Cohen's *d* effect size.
* p < .05
**p < .01

CHAPTER 5: DISCUSSION AND CONCLUSIONS

Introduction

The present study examined whether ImPACT demonstrates sufficient convergent, discriminant, and diagnostic validity to be used as a post-concussion cognitive measure when compared to a traditional paper-and-pencil neuropsychological screening battery. These issues will be discussed in turn.

ImPACT Convergent Validity vs. Neuropsychological Tests

Evidence of convergent validity was examined by comparing ImPACT Domains with theoretically convergent measures. ImPACT Verbal Memory demonstrated nonsignificant correlations with the corresponding paper-and-pencil measure, CMS Dots. While initially surprising, this lack of convergence may be secondary to shortcomings of the CMS Stories subscales. CMS Stories did not differentiate between groups and did not correlate with other measures, demonstrating suboptimal performance. It is possible that ImPACT Verbal Memory may have shown convergence with more traditional rote memory tasks if assessed, such as California Verbal Learning Test- Children's Edition and other similar tasks. However, when ImPACT Verbal Memory is examined qualitatively a potential weakness becomes apparent. While traditional verbal memory tasks often consist of orally presented verbal stimuli followed by short-delay recall, long-delay recall, and recognition memory, ImPACT Verbal Memory appears to rely more upon recognition discrimination, or choosing the target word from a subset of options. This overreliance on recognition discrimination and comparative lack of free recall appears to be a limitation of ImPACT Verbal Memory.

Of the ImPACT domains, Visual Memory was the only measure to demonstrate significant correlations with its corresponding paper-and-pencil measure, CMS Dots. This convergence indicates the likelihood that both ImPACT Visual Memory and CMS Dots assess the same underlying construct, thought to be visual learning and memory.

Both ImPACT Visual Motor Speed and ImPACT Reaction Time demonstrated small, nonsignificant correlations with the theoretically corresponding measure, TMT A. These ImPACT domains did show convergence with other measures that also contained a timed motor component. Each of the ImPACT domains also demonstrated unexpected convergence with paper-and-pencil tests that included an executive component. Overall, the ImPACT domains demonstrated variable convergent validity with the best support for ImPACT Visual Memory.

ImPACT Discriminant Validity

Overall, ImPACT domains demonstrated limited evidence of appropriate discriminant validity. All of the ImPACT domains were significantly correlated with each other at moderate to large effect sizes. These results were similar to those of Maerlender et al.'s (2010) results of 54 male athletes ages 17 to 22, indicating convergence across studies. Further, each of the ImPACT domains demonstrated significant correlations with measures of purportedly different underlying constructs. For instance, ImPACT Verbal Memory demonstrated large correlations with two executive functioning measures (TMT B and D-KEFS Design Fluency) and a medium correlation with a visuospatial construction measure (Beery VMI). ImPACT Visual Memory also demonstrated medium to large correlations with TMT B and D-KEFS Design Fluency, a large correlation with Beery VMI, and moderate correlations with two expressive language measures (FAS and Animals). ImPACT Visual Motor Speed demonstrated a moderate correlation with Beery VMI and large correlations with D-KEFS Design Fluency, FAS, and Animals. Finally, ImPACT Reaction Time demonstrated moderate correlations with Animals and Beery VMI and large correlations with FAS and D-KEFS Design Fluency. These results were unexpected and may suggest that ImPACT constructs are less specific than is ideal with potentially problematic method variance.

Discriminant validity analyses using the Maerlender et al. (2013) formula demonstrated that all four of ImPACT domains were at least moderately correlated, suggesting significant method variance. The current ImPACT results are generally consistent with Maerlender et al.'s (2013) findings with the exception that the previous study results suggested ImPACT Reaction Time demonstrated adequate discriminant validity. Maerlender et al. (2013) previously concluded "three of the four ImPACT composite scores were not sufficiently distinct to support specific construct-oriented interpretations" (p. 290). The current findings generally confirm this assertion and further indicate the possibility of ImPACT's fourth domain also lacking in specific construct-oriented interpretations.

The current study's neuropsychological screening battery results were not consistent with the Maerlender et al. (2013) findings. Surprisingly, results demonstrated that the neuropsychological screening battery composites also demonstrated insufficient support for construct-specific interpretations. Several potential explanations may be offered for these discrepant neuropsychological screening battery findings. As noted previously, criteria for a screening battery are less well-established for adolescent athletes with little evidence for specific measures within a concussion battery. The current study’s measures were established from an a priori clinically derived screening battery that included CMS Stories. As noted previously, CMS Stories underperformed in all areas (convergent, discriminant, and diagnostic validity). Inclusion of this test in the multiply-operationalized composites may have added additional variance. Another explanation is also possible, in which one must consider the nature of test score clusters in a healthy sample. In healthy individuals, general abilities tend to correlate. For instance, an individual with average-range verbal memory is likely to also score within the average range on other neuropsychological domains. The current sample appears to conform to expected ranges for a healthy sample, in that generally average-range test scores correspond across domains. Such a sample could potentially “wash out” discriminant findings when mono-method multiply operationalized discriminant validity coefficients are calculated.

Overall Domain Specific Inferences

Verbal Memory

While ImPACT Verbal Memory differentiated successfully between concussed and healthy athletes, it demonstrated questionable convergent and discriminant validity. These results indicate the likelihood that the ImPACT Verbal Memory domain is confounded by an underlying factor that is unrelated to verbal memory. This underlying factor also appears to be measured by the three other ImPACT domains and non-verbal measures with visuomotor components (TMT B, D-KEFS Design Fluency, and Beery VMI), all of which demonstrated strong correlations with ImPACT Verbal Memory. Of note, these convergent measures all possess an underlying visual, motor, or visuomotor component and many include a timed component. Results from the current study are similar to Maerlender et al.'s (2010) analyses of verbal memory discriminant validity in that ImPACT Verbal Memory demonstrated significant inter-correlations with other ImPACT domains, albeit with more moderate effect sizes in the previous study. In contrast, Maerlender et al. (2010) found that ImPACT Verbal Memory demonstrated appropriate convergence with other verbal memory measures; Verbal Memory was previously moderately correlated with only one discriminant measure, namely an aspect of a visual memory task. The current study offers more extensive information regarding correlations with additional discriminant nonverbal tasks, leading to increased concern regarding a nonverbal underlying component.

Visual Memory

ImPACT Visual Memory differentiated successfully between concussed and healthy athletes and demonstrated appropriate convergent validity, with moderate to large correlations with all CMS Dots subscale scores. These results support the Maerlender et al. (2010) findings. However, discriminant validity analyses were less promising, with large correlations found between ImPACT Visual Memory and two other ImPACT domains (Verbal Memory and Visual Motor Speed). ImPACT Visual Memory was also correlated with all five theoretically discriminant measures.

Processing Speed

Both ImPACT Visual Motor Speed and ImPACT Reaction Time differentiated successfully between concussed and healthy athletes. While the measures were not correlated with the criterion convergent measure, TMT A, both measures were correlated with each other and with additional executive measures that contained a speeded component (TMT B and D-KEFS Design Fluency). In this respect, both ImPACT Visual

Motor Speed and ImPACT Reaction Time appear to be suitable measures of processing speed and/or reaction time. However, discriminant validity analyses were less promising, with notable significant correlations between these two ImPACT domains and all discriminant validity measures.

Overall, ImPACT Visual Memory was the only ImPACT domain with significant correlations with the associated convergent measure. While ImPACT Visual Motor Speed and ImPACT Reaction Time were not correlated with the selected convergent measure, they were correlated with each other and additional speeded measures demonstrating support as processing speed measures. The remaining ImPACT Verbal Memory domain demonstrated poor convergent and discriminant validity evidence. Notably, all of the ImPACT domains were highly inter-correlated with large effect sizes with the exception of the moderate relationship between Visual Motor Speed and Visual Memory. These results indicate the strong likelihood of method variance and the potential of a similar underlying construct likely of a visuomotor nature. Alternatively, the underlying factor may be related to test medium. Specifically, an underlying visuomotor component may be an artifact of computerized testing. This artifact appears most strikingly in the Verbal Memory domain. Unlike traditional verbal memory measures that are typically administered through auditory means with repetition of orally presented verbal lists or stories, computerized verbal memory tests necessitate a visual component to view stimuli and a motor component to manipulate the test trials and presentation. ImPACT Verbal Memory does not appear to adequately control for these confounding elements. Determining the effects and confounds of computerized testing is a necessary next step in assessing appropriateness and validity of computerized measures.

Additionally, when ImPACT Verbal Memory is examined qualitatively, reliance upon recognition discrimination becomes apparent. The ImPACT Verbal Memory measure, along with the battery as a whole, would likely be strengthened by increased emphasis on immediate and delayed free recall components. It appears that clinical use of ImPACT may be best supplemented with an additional brief verbal memory measure to bolster verbal memory inferences.

Diagnostic Validity

Sensitivity and Specificity

Examination of diagnostic validity analyses demonstrated that sensitivity rates for most measures, regardless of cut scores used, were low. However, ImPACT had a median sensitivity rate of .36 compared to the neuropsychological screening battery median sensitivity rate of .14. Specificity rates were adequate for both ImPACT and the neuropsychological screening measures. These results suggest that ImPACT was more sensitive to borderline impairment (T-score $\leq$ 36) following concussion than the traditional screening battery. This sensitivity rate becomes more compelling when the variability of concussion symptoms is considered along with the inherent difficulty in measuring and tracking such heterogeneous symptoms. It is likely, if not probable, that most concussions do not cause prominent enough cognitive deficits to be detected using cognitive measures. As such, both computerized and traditional measures may fail to detect subthreshold cognitive difficulties as the subjective complaints following concussion often overshadow the objective, or measureable, deficits following concussion. Additionally, the wide variability in presenting symptoms following concussions means that only a small proportion of injuries will result in prolonged cognitive difficulties. Scientifically, this may be good news for athletes sustaining concussions in that most cognitive difficulties are not likely to reach a clinically significant level of impairment. If this is the case, cognitive testing may simply reinforce the likelihood of a good outcome and educate individuals with concussion, namely that in most cases the brain remains healthy and capable of processing information, attending to information, encoding new information, and retrieving information over time. However, it some cases cognitive symptoms may be more profound and warrant additional attention. In such cases, it appears that ImPACT may be an appropriate screening tool and/or baseline tracking tool to help determine whether perceived cognitive deficits warrant additional testing.

Classification Accuracy

When test scores were examined to determine clinical diagnostic validity through categorical assignment, the ImPACT domains demonstrated adequate ability to correctly classify healthy athletes as defined by the absence of any borderline impaired test scores ($T \leq 36$). However, only slightly more than half of the concussed athletes were correctly categorized by the ImPACT domains at this cut score. When the threshold for diagnostic classification was more rigidly defined by the presence of impaired test scores ($T \leq 29$), ImPACT correctly classified almost all of the healthy athletes while less than a third of concussed athletes were correctly classified. In contrast, the neuropsychological screening battery correctly classified a larger proportion of concussed athletes at $T \leq 36$ than ImPACT.

Potential explanations exist for the discrepancies in athlete categorization between tests. It is possible that the screening battery both detected more deficits at a borderline impaired threshold and misclassified healthy athletes as the result of a Type I error. Namely, because the screening battery had several additional domains there were more opportunities for impaired scores and implied deficits through chance alone. However, it is also possible that the screening battery's inclusion of domains not addressed by the ImPACT battery led to the detection of true deficits that might be missed by the ImPACT domains. In order to address possible concerns related to both batteries independently, the ImPACT scores and the screening battery were combined to provide a fuller neuropsychological battery. When these domains were combined, the majority of concussed athletes were classified correctly at a cut score of 36T or lower. At 29T or lower, fewer than half of the concussed athletes were correctly classified. While the 36T cut score resulted in more false positives with a large proportion of healthy athletes misdiagnosed as concussed, the number of deficits correctly detected indicates that there may be benefits in using a fuller neuropsychological battery that includes both computerized and traditional measures. This is especially true in cases where an initial screening battery, such as ImPACT, indicates cognitive deficits that may warrant further assessment by a neuropsychologist.

As noted earlier, significant post-concussive cognitive changes are less common than other symptom complaints. However, current results indicate that ImPACT does appear to adequately detect the presence of cognitive change post-concussion as evidenced by ability to differentiate between healthy and concussed athletes and sensitivity to the detection of borderline impaired cognitive scores. Using such a screening tool is essential in creating an algorithmic approach for assessing potential cognitive symptoms post-concussion. This approach includes a baseline screening followed by more complete post-concussion testing if necessary, ensuring that athletes who exhibit cognitive changes are more likely to be detected, tracked, and assisted with return to cognitive baseline. Such testing is consistent with Echemendia et al.'s (2011) position paper on the role of neuropsychologists in evaluation and management of sports concussions and will further complement the sports physician's prescription of return-to-play decisions.

Limitations

Significant group differences in the areas of reading skill/premorbid estimate of intelligence and sport at time of evaluation limit the ability to generalize results from the current study. As noted earlier, the control group demonstrated significantly higher WRAT-4 Reading scores, indicating a potentially higher premorbid level of intelligence. This difference may generalize to overall superior academic achievement and test-taking skills in the healthy athlete controls. If the control group is indeed more intelligent and/or academically skilled, participant selection bias may have contributed to this group difference. The controls represent a self-selected sample that likely attracted a small subset of parents and athletes concerned about sports concussion. Method of selection occurred through flyers circulated via participating club teams, local gyms, and private email listservs. Such recruitment methods may have attracted parents and participants of a higher socioeconomic status who had access to the flyers through club teams and the means and ability to travel to the University of Kentucky for assessment. However, an alternative possibility may account for the reading/premorbid estimate group differences. It is possible that the group differences noted in this study are representative of true cohort differences between healthy athletes and athletes who have the propensity to experience persistent concussion symptoms. As noted previously, premorbid factors play a large contributing role in concussion outcomes. Additionally, research (e.g., Stavinoha, Butcher, & Spurgin, 2011) indicates that intact brain reserve capacity contributes to a healthy, full recovery following brain injury. As such, it is possible that premorbid intelligence and the resulting brain reserve capacity are protective factors for concussions. If present in the control group, such protective factors may have minimized the extent of damage during cranial contact resulting a higher threshold for experiencing concussion symptoms (i.e., less likely to experience concussion with same blunt force trauma). The higher premorbid intelligence estimates for the control athletes may indicate a higher baseline cognitive reserve that protects the brain's cognitive and functional capacities when compared to the concussion group. Further, as noted previously Moser, Schatz, & Jordan (2005) indicated that concussions in younger athletes may affect overall cognitive ability, including intelligence. In their research, asymptomatic athletes who had recovered from two or more concussions demonstrated similar performances to currently concussed (i.e., symptomatic) peers on neuropsychological tests; the athletes with cumulative concussions also demonstrated lower grade-point averages than their single-concussion and non-concussed peers (Moser, Schatz, & Jordan, 2005). Of note, more participants in SPORT had experienced concussions prior to the index concussion, with a modal experience of one prior concussion, further supporting the possibility that multiple concussions may impact intelligence in younger athletes.

Qualitative group differences in sport played at time of evaluation were also noted. However, groups were evaluated for differences between current sport at the time of evaluation only. Information regarding additional sports was not available for the complete sample; it is likely that athletes in the middle school and high school age ranges play multiple sports that vary depending upon the season. As such, seasonal group differences may not reflect true group differences between athletes in various contact sports.

Another issue is that the current study did not utilize performance validity measures. Lack of performance validity measures is generally comparable to real-world concussion baseline testing sessions, in which healthy athletes generally do not exhibit test results lower than normal limit ranges (i.e., baseline results are often low average or higher). However, research (e.g., Iverson, G.L. & Schatz, 2015; Schatz & Glatts, 2013) has suggested the possibility that athletes may "sandbag" preseason testing to produce under-representative test scores and indirectly facilitate later return-to-play decisions. While Schatz and Glatts (2013) demonstrate that sandbagging may be detectable using ImPACT, the possibility remains that athletes may intentionally under-represent their cognitive capacity during baseline testing. These lower test scores may allow for quicker return-to-play decisions if cognitive declines are not demonstrated through testing. Increased awareness of possible underestimation of baseline cognitive results is necessary, and may require the inclusion of brief performance validity assessments in those measures designed for baseline testing and serial testing following concussion.

Additionally, small sample sizes may diminish external generalizability and potentially limited appropriate analyses. For instance, a factor analysis indicative of underlying constructs within the testing battery was not possible due to limited sample sizes. However, achieved power analyses indicated adequate ability to detect group differences for the neurocognitive measures. Additionally, many of the effect sizes found were large. Future research should attempt to replicate these findings in order to substantiate findings from the current study.

Given the use of a pre-selected clinical battery, convergent and discriminant measures were not selected specifically for the current study. Use of an archival clinical group with a previously selected battery dictated matched tests for the control group. While additional memory, processing speed, and reaction time measures would have increased the findings' strength, many findings remain robust. For instance, the interrelationship between ImPACT domains was clearly not affected by comparison test selection and instead offers evidence for method variance within the ImPACT battery. Further, findings from the current study are consistent with Maerlender et al. (2010), who demonstrated ImPACT's generally adequate convergent validity in comparing ImPACT's factor loadings to that of a traditional paper-and-pencil battery. Maerlender et al.'s (2010) research demonstrated convergent validity for three of the four constructs. Similar to the current study, Maerlender et al. (2010) recognized that ImPACT is a useful screening tool, but suggested that other sources of data are necessary to detect and manage concussions.

Finally, the current study was limited to chronic post-concussion symptoms. Thus, current results are generalizable only to adolescents with similar presentations. The current results are not intended to assess ImPACT's validity for use as an immediate assessment.

Implications

This study demonstrates appropriateness of ImPACT assessment following concussion, as results indicate that each domain is able to differentiate between concussed and healthy athletes. Additionally, all domains except ImPACT Verbal Memory indicate appropriate convergent validity. At present, ImPACT does appear to be appropriate for use as an initial screening tool. ImPACT has the potential for further utility if the Verbal Memory domain is strengthened in future versions by adding/strengthening immediate and delayed verbal memory domains. Overall, the widespread use of ImPACT highlights a contemporarily relevant issue in the field of neuropsychology. As ImPACT and other computerized measures gain popularity, they represent a trend towards adoption of computerized cognitive testing. Not only is computerized testing becoming popular in neuropsychology, but it has also increased in use for achievement and standardized tests. Adolescents and children are a particularly relevant group in this testing paradigm shift, as they are becoming increasingly adept with computerized learning and testing in academic settings from a very young age. This routine use of technology in childhood and adolescence further indicates the necessity of fully validating newly developed tests. While these measures may have less utility in older populations, more research is needed to determine the appropriateness of increased computerized neurocognitive test options, especially for use with children and adolescents.

APPENDICES

Appendix A. Telephone Screener

Validity of Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT): Construct validity and Diagnostic Validity in a Sports Concussion Sample

Athlete Name: ______________________________
Parent Name: _______________________________
Date of screener: ____________________________
We are conducting a research study about thinking problems following sports concussion. Eligible participants include athletes who play a contact sport, such as football, soccer, lacrosse, rugby, among others, who are between the ages of 12 and 16. Eligible athletes have not experienced a concussion in the past year. If your child is eligible for the study, the two of you will attend one 2-3 hour testing session at the University of Kentucky. Following testing, we can mail you a copy of results that may be used as pre-season testing for your child's sport. If your child should sustain a concussion, these results will be useful to present to the attending physician. Today, I will be asking some voluntary screening questions regarding mental health and medical history to determine if your child is eligible. Do you have time to answer these question? (Y/N) *If yes…* As a voluntary participant, I would like to briefly review your rights. All the information you provide is strictly confidential and is accessible only to research team members and individuals who may audit our work for integrity purposes. There are no foreseen risks or benefits to participating in this study. As a voluntary participant, you can choose to revoke your consent at any point. Finally, if you have any questions or concerns I can provide contact information for the Office of Research Integrity at UK (859-257-1639). Do you have any questions before we begin?

1. How old is your child? __________
2. What is their sex? _____________
3. What grade is your child in? _______________
4. Have they ever skipped or repeated a grade? _______________________
5. Has your child ever attended special education classes or had an individualized education plan put into place? _____________________________
6. What type of grades does your child make in school (i.e., A's, B's C's)?_____________
7. Has your child ever been diagnosed with a concussion? (Potential follow-up: Has your child ever hit his or her or head hard enough to see stars or been knocked unconscious?) ______________ If yes, when?_______________________
8. Does your child have any psychological diagnoses, including depression, anxiety, or ADHD? _______________
9. Has your child ever been diagnosed with a neurological disorder?__________

If your child is eligible for the study, what is the best phone number and time to reach you? _______________________________
What days and times typically work best for you and your child to come to the University of Kentucky for a 2.5 to 3 hour assessment? ____________________________________

Appendix B. CONT Demographics Form

ID: ___________________________

Date:__________________________

1. Age: __________
2. Sex: M/F
3. Race/ethnicity: _______________
4. Current Year/Grade in school: _____________
5. Handedness: ___ Right ____ Left – familial? Y/N
6. Skipped or repeated a grade? Y/N Specify: _______________________
7. Special education classes or individualized education plan? Y/N *(If yes, discontinue)*
8. Grades in school (i.e., A's, B's C's)? _____________
9. Concussion history? Y/N Date: _____________
    a. In past year? Y/N *(If yes, discontinue)*
    b. Details: (Loss of consciousness? Duration of symptoms? Medical attention?)
    ____
    ____
    __
10. Participant psychological history (diagnosed with depression, anxiety, ADHD, etc.)? Y/N *(If yes, discontinue)*
11. Participant neurological history? Y/N *(If yes, discontinue)*
12. Family psychiatric history: Y/N Specify:_______________________
13. Family neurological history: Y/N Specify:______________________
14. Sport(s) played and experience length (i.e., years or seasons):
    ____

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Educational Institutions

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Professional Positions

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Jesse G. Harris Scientist-Practitioner Award (2015)
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Professional Publications

Berry, D.T.R., Harp, J.P., **Koehl, L.M.** & Combs, H.L. (in press). Applying diagnostic standards to performance validity tests and the individual case. In S.C. Bowden (Ed.) *Neuropsychological assessment in the area of evidence-based practice: Diagnostic and treatment evaluations.* New York: Oxford University Press.

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