Development and Preliminary Testing of the Concussion Assessment Web App Tool

by

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Abstract

Introduction: Identifying and monitoring the resolution of cognitive impairment following sport-related concussion and providing objective information for clinical return-to-play decisions is crucial, particularly for contact sports. Many concussion symptoms do not appear immediately, and the sports person would need to be monitored and re-tested over time, however most sport teams do not have the luxury of readily available medical staff. Therefore, this study presents the process of developing a novel web-based neuropsychological test battery App for concussion, and the subsequent determination of sensitivity, reliability, and repeatability as a first step in validity and reliability testing.

Subjects and design: Neuropsychological baseline data was collected on 11 healthy male volunteers (mean age = 22 ± 2.5 years). Repeat data was collected pre- and post-fatiguing exercise for sensitivity, and further tests for diurnal variation included three daily repeat assessments (morning: 0700 ± 2 h; afternoon; 1400 ± 2 h; evening: 1900 ± 2 h) over a five-day period.

Measurements: The administration of the Concussion Assessment Web-App tool (CAWA) included six tests as a part of a test battery. These included concussion red flag questions, a self-report inventory of neuropsychological symptoms; The Concussion Symptom Inventory (CSI), as well as a series of four cognitive sub-tests: Simple Reaction Time, Complex Reaction Time, Digit Span Backwards, and Auditory Reaction Time.

Results: The results indicate that the CAWA battery is sensitive to the effects of treadmill-based maximal exercise, with no diurnal variation in asymptomatic participants.

Conclusions: Prior to any field trials, the CAWA preliminary findings indicate that the individual elements are sensitive and are repeatable in an asymptomatic population. The CAWA is an easy, time-efficient, and cost-effective method for individuals to test and re-test multiple times to identify latent signs / symptoms and neurocognitive trauma following sports-related concussion.

INDEX WORDS: Concussion, Sports Related Concussion, Self-Reported Symptoms, Concussion Assessment Tool

Preface

The basis of this research was discussed in length with supervisors Dr. Sally Lark and Associate Professor Wyatt Page, who had the idea for a concussion web-App. The discussion comprised of what should be included in the web-App in the assessment for concussion injury. The student's contribution to the study entailed independent research for web-app inclusion and background, discussion and contribution to technological problems (see Chapter 4.), participant recruitment, and independent data collection and initial analysis from which the results and implications were discussed.

Acknowledgements

Firstly, I would like to thank each of the participants for the time and effort they contributed to the study. Their willingness to accommodate the requirements of the study into their already busy schedules was much appreciated. Furthermore, it was refreshing to experience the positive attitude towards the Web-App and the patience provided by all involved throughout the development process. I would like to express my sincere gratitude to each participant and trust that participation was both enjoyable and interesting.

I would also so like to acknowledge the guidance and expertise of my supervisors Dr. Sally Lark and Associate Professor Wyatt Page. Their combined professional standards and attention to detail was vital to maintaining a consistent effort in striving for excellence in all areas of the study.

The Massey University Human Ethics Committee: (Southern A, Application 16/32) approved the testing procedure and written consent was obtained from all participants prior to commencing the study.

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List of Abbreviations

ART	Auditory Reaction Time
CAWA	Concussion Assessment Web-App
CISG	Concussion in Sport Group
CNT	Computerised Neuropsychological Test
CRI	Concussion Resolution Index
CRT	Complex Reaction Time
CSI	Concussion Symptom Inventory
GXT	Graded Exercise Test
ImPACT	Immediate Post-Concussion Assessment and Cognitive Test
mTBI	Mild Traumatic Brain Injury
NP	Neuropsychological Assessment
PCS	Post-Concussion Syndrome
SCAT	Sport Concussion Assessment Tool
SIS	Second Impact Syndrome
SRC	Sports-related Concussion
SRT	Simple Reaction Time
TBI	Traumatic Brain Injury
WM	Working Memory

Chapter 1. Introduction

Sport-related concussion is a common injury, which can be explained as a complex pathophysiological process affecting the brain, leading to an alteration in mental status and neurological function (Daneshvar, Nowinski, McKee, & Cantu, 2011). The term used in sporting circles and often reported by media as a 'knock to the head', is grouped under a subset of mild traumatic brain injuries (mTBI), categorised as sports-related concussion (SRC) (King, Hume, Gissane, Brughelli, & Clark, 2016). A concussion is a common occurrence at all sporting participation levels, especially in football codes. Alarming concussive incidence rates have recently been recorded in Rugby Union (New Zealand's national sport) at all sporting levels (Cross, Kemp, Smith, Trewartha, & Stokes, 2015; Archbold et al., 2017; Hollis et al., 2009). Despite its frequency, a concussion is largely under-reported; in New Zealand, 62% of high school rugby players were shown to have not reported a concussion to a medical practitioner (Sye, Sullivan, & McCrory, 2006). Additional concern is mounting regarding the long-term consequences of unidentified cumulative head impacts. Recently, the detrimental effects of the second-impact syndrome (SIS) have been identified; the occurrence of a second devastating head injury before recovery of the former. The effects of SIS are particularly worrisome for the youth where developing brains are more likely to be susceptible to the effects of concussion in comparison to an adult (Moser & Schatz, 2002). For this reason, the need for more frequently administered assessments for youth athletes (college and earlier) has been recognised due to athletes between 8-15 years of age being in a stage of rapid cognitive maturation for which annual testing is advised (Buzzini & Guskiewicz, 2006). The increasing amount of awareness is also reflected in the current concussion management protocols devised by the most recent consensus statement (2017) released by the Concussion in Sport Group (CISG) (McCrory et al., 2017). Proposed as a tool for incidence rate reduction, the implementation of a pitch-side concussion assessment (PSCA) was introduced by the International Rugby Board (Fuller, Kemp, & Decq, 2014). The PSCA saw a considerable decline in the number of concussed athletes remaining on the field of play from 58% to 15% in elite level performance. However, due to a lack of pitch-side medical personnel, such a tool/process is yet to be implemented at the amateur level. The information above provides a scope of the need for evaluation and management of sport-related concussion.

The current best-practice for immediate pitch-side care following a concussion mandates that once an athlete is diagnosed with a concussion, he/she is removed from the field of play and should not be allowed to return-to-play until cleared by a sports medicine professional (McCrory et al., 2017). Upon removal, the athlete is immediately subjected to an in-depth battery of assessments via a multidisciplinary group of trained concussion medical professionals including physicians, physical therapists, and athletic trainers (Okonkwo, Tempel, & Maroon, 2014). The assessment includes a multi-model objective evaluation useful in differentiating concussed from non-concussed athletes, while also excluding more severe brain injury; a critical determinant of immediate decisions for the athletes (Okonkwo et al., 2014; Putukian et al., 2013). The assessment includes the presence of typical signs and symptoms that can be broadly characterised as motor (e.g., balance or gait impairments) and non-motor symptoms. Non-motor symptoms may include: physical (i.e. a headache, nausea, photosensitivity); cognitive (memory, executive function, visuospatial, or attention deficits); sensory (visual, vestibular, or proprioceptive deficits), emotional (i.e. irritability, nervousness, sadness); or sleep-related (i.e. disturbed sleeping patterns, drowsiness) (Halstead & Walter, 2010). The multifaceted approach was recommended as no single measure has solely demonstrated efficacy in the monitoring of the resolution of concussion symptomology (Hobbs, Young, & Bailes, 2016; McCrory et al., 2017).

A concussion is an evolving injury in the symptomatic phase, with rapid development and changing of clinical signs and symptoms. To this end, recommendations provided in "*Consensus statement on concussion in sport*", generated during the 5th International Conference in Sport suggest that a key concept in the side-line assessment is the rapid screening for a suspected SRC, as opposed to a definitive diagnosis (McCrory et al., 2017). As such, numerous pitch-side assessment tools are available which aid sports medicine professionals detect and measure the mental status of the injured athlete. Currently, the gold standard for rapid screening is the Sport Concussion Assessment Tool (5th version; see Appendix D); a pen-and-pencil multi-dimensional test instrument which includes tests such as the Maddocks' questions (Maddocks, Dicker, & Saling, 1995), a signs and symptoms checklist, and the Standardised Assessment of Concussion (McCrea et al., 1998). There are reported concerns about the use of instruments like the SCAT. Specifically, the lack of awareness regarding the availability of standardised testing platforms, and inconvenience (Curaudeau, Sharma, & Rovin, 2011). The inconvenience can be attributed to its use in impractical situations (e.g. pen and pencil use in poor weather conditions), and dissemination of the test scores is vastly more difficult. It is also worth mentioning that orientation questions used in the SCAT have proven unreliable in the sporting context when compared with cognitive assessments (e.g., memory) (McCrory et al., 2017).

In addition to a rapid screening process, research has been directed toward the detection and symptom resolution monitoring of cognitive processes via neuropsychological examination. Since the early 1990's NP examination has been considered an essential component in the assessment of concussion and since has been labelled the 'cornerstone of concussion management' by the CISG (Aubry et al., 2002). Several cognitive functions are reported susceptible to impairment following a concussion which include: decreases in reaction time (Maddocks et al., 1995; Warden et al., 2001); information processing speed (Barth et al., 1989); attention (Cicerone, 1997; Pontifex et al., 2012), and; memory (Lovell & Collins, 1998). More recently, auditory processing has also been identified as prone to dysfunction following sports concussion injury (Białuńska & Salvatore, 2017; Turgeon, Champoux, Lepore, Leclerc, & Ellemberg, 2011). Detecting the cognitive symptom changes among athletes is best accomplished using a baseline approach for comparative purposes. The advantages of collecting individual baseline scores are associated with the objective ability to detect and document subtle changes in post-concussion follow-up assessments, and recovery to baseline levels, so cognitive functioning can be tracked. One significant issue with this approach is the amount of time consumed when obtaining individual data at pre-season for a team comprised of 30-40 athletes. Typically, neuropsychological assessment is facilitated by a neuropsychologist in a face-to-face, one-on-one format requiring long periods of time to conduct the evaluation (>30-minutes per athlete). Following a concussive event, tests must then be scored, analysed, and interpreted; all of which must be carried out by a trained professional. Subsequently, follow-up assessments succeeding a concussion must be scheduled, limiting the ability to detect subtle changes in cognition commonly seen in the acute stages of a developing sports concussion injury. Collectively, these issues hinder the athlete trainer/sports medicine professional's ability to use the results in a timely fashion.

With advancements in technology, computerised assessment tools have made their way into the market. The contention that use of computerised neuropsychological test batteries is gaining momentum is supported by the CISG amongst other international medical associations (Allen & Gfeller, 2011). Several computer-administered software systems are currently available such as the Concussion Resolution Index (CRI), Head-Minder: CogSport (Collie, Maruff, Makdissi, et al., 2003), and the Immediate Post-Concussion Assessment and Cognitive Test (Iverson, Lovell, & Collins, 2003). The development of computerised assessment measures has been proposed as a way of confronting challenges of logistical, practical, psychometric, and statistical inadequacies associated with traditional tests and is being used at a wide range of sports and levels of play (Allen & Gfeller, 2011). Several researchers have outlined the advantages of computerised neuropsychological assessment over traditional measures which include: reduced financial costs; decreased medical staff requirements; efficient data collection and storage for later clinical or research access; high sensitivity to subtle cognitive effects and the ability to demonstrate the extent of cognitive malfunction during the recovery period, and; the ability to evaluate large groups of athletes without the need for an excessive number of persons (Broglio, Ferrara, Macciocchi, Baumgartner, & Elliott, 2007; Collie, Darby, & Maruff, 2001; Collie, Maruff, McStephen, & Darby, 2003; Johnson, Kegel, & Collins, 2011; Makdissi et al., 2001; Schatz & Browndyke, 2002; Shuttleworth-Edwards, 2011). Computerised assessment also offers an important advantage of efficiently obtaining individual or team baseline assessments. However, a well-known and longstanding issue with computerised neuropsychological test batteries is related to the reliability of repeated measures and the sensitivity of statistical analysis. This concern is founded on various problems associated with practice effects, regression to the mean, and test-retest reliability using the baseline model for repeatability (Erlanger et al., 2003). Test-retest reliability is infrequently provided for many tests used in sports concussion assessment and reported reliability estimates are derived from relatively long between-test time intervals (Broglio, Ferrara, Macciocchi, Baumgartner, & Elliott, 2007; Collie et al., 2003; Elbin, Schatz, & Covassin, 2011; Erlanger et al., 2003; Miller, Adamson, Pink, & Sweet, 2007; Schatz, 2010; Schatz & Ferris, 2013). Sensitive and reliable tools are valuable assets in athletic settings, where damage to the brain may be developing and worsening symptoms during the symptomatic phase of the recovery period.

The initial, yet limited success in this area has led to increasing calls for the development of a reliable and sensitive multi-faceted concussion assessment battery that assists in the identification and management of SRC. Accordingly, in the present study, we set out to develop a battery of concussion assessment tests into a self-administered app for use on portable devices that have high sensitivity to detecting concussion symptoms, and high inter-individual reliability. The Concussion Assessment Web-App (CAWA) is designed for use by non-medically trained individuals, for immediate evaluation of suspected sports-related concussion. Our findings provide evidence of a reliable and sensitive tool for administering to athletes when cognitively impaired.

Chapter 2. Development of the Concussion Assessment Tool

Prior to developing the concussion assessment tool, we sought to address several identified problems associated with current concussion assessment protocols. The initial objective was to develop a rapid test battery, lasting less than 7-minutes, which would be sensitive to various levels of cognitive impairment (see Chapter 5 for more information on the development of the Web-App). In addition to administration time, several important and desirable functions as well as some high-level specifications were identified for inclusion in the development process.

1) Accessibility: Can be self-administered and used by multiple people at the same time
2) One implementation: Runs in a browser and will work on any device - mobile, laptop, different Operating Systems etc. with the main target being smart phones.
3) Work-online/offline: Works locally when there is no network connection and then next time it is used, and a connection is available, automatic uploads the data.
4) Ease of use: A brief instruction page is to precede each assessment task. All of which are basic tasks.
5) Secure registration: Participants register, and their details are secure in a cloud database.
6) Secure local data: An encrypted local database is run of the device and new data uploaded to the cloud database when an internet connection is available
7) Engagement: Randomised test order and timing to keep participants engaged and minimise habituation
8) Detail logging: Each time a participant runs through the tool, results are logged, including: 1. Assessment Tool version #; 2. Device details (e.g., Samsung G6); 3. Temperature; 4. Start time; 5. For each task log: Version #; Time to complete; Results; 6. End Time
9) Server-side-reporting: Simple reporting capability out of the encrypted cloud database. This could be as simple as running a backend script and extracting all

data from the current database into a spreadsheet. Or providing a user's email address and extracting just their data to a spreadsheet.

10) Multi-dimensional approach: Determine and quantify the vast array of signs and symptoms and neurocognitive impairments associated with sport-related concussion. Consequently, we designed the tool by incorporating the most relevant and up-to-date components of several current concussion assessment tools. The basic stages of the tool include:

A. Sign-in / welcome screen
B. Concussion 'red-flags' assessment task - A series of seven (7) 'yes/no/unsure' questions presented in a standard order
C. Concussion-Symptom-Inventory task - A series of twelve (12) questions presented in random order where the participant responds on a 7-point Likert scale 0-6 (0 = no symptoms, 3 = moderate symptoms; 6 = severe symptoms). This component was adopted from the Sport Concussion Assessment Tool.
D. The next four stages are presented in random order (for more information on these tasks, see Chapter 5):
    - Psychomotor-Vigilance-Test (simple visual reaction time) task
    - Motor-Praxis-Test (complex visual reaction time) task
    - Digit-Span-Backwards (working memory) task
    - Auditory-Vigilance-Task (simple auditory reaction time) task
E. Thank-you-screen - Finishes with this page and they are automatically signed out.

2.1 Hypothesis

H_1: There will be diurnal variation with testing

H_0: There will be no diurnal variation with testing

H_1: The cognitive tests will be sensitive to fatigue in asymptomatic persons

H_0: The cognitive tests will not be sensitive to fatigue in asymptomatic persons

Chapter 3. Literature Review

3.1 Sports related concussion and epidemiology

Since Rugby Union (henceforward termed rugby) first became an openly professional sport in 1995, increases in participation rates, particularly at the non-professional level, have soared with more than 6.6 million players spanning 120 countries around the globe (Bathgate, Best, Craig, & Jamieson, 2002; Garraway, Lee, Hutton, Russell, & Macleod, 2000). With the ever-increasing interest in the sport, a growing concern also surrounds the high risk of sporting injury. Injury incidence rates have climbed with professional athletes seeing a substantial increase to around 80 injuries per 1000 playing hours (Bathgate et al., 2002). At the crux of such a high incidence rate lies traumatic brain injury, also known as a sport-related concussion (Archbold et al., 2017). Sport-related concussions are of increasing concern for sport/recreation participation at all levels, a trait shared with many contact and collision sports including American Football (Guskiewicz et al., 2003), ice hockey (Echlin et al., 2010), soccer (Yard, Schroeder, Fields, Collins, & Comstock, 2008), and equestrian riding (Fuller, Taylor, & Raftery, 2015). This is illustrated in rugby with some studies reporting incidence rates of concussion (Archbold et al., 2017; Cross et al., 2015; Fuller et al., 2015; Hollis et al., 2009; Kemp, Hudson, Brooks, & Fuller, 2008).

One noteworthy study was published by Cross et al. (2015) who collected injury incidence data for 810 players at the highest level of club rugby over two playing seasons (2012/ 2013 and 2013/2014) in the English Premiership. This was the first study to consider the short and medium term post-concussive effects in professional Rugby Union players. Over this period 8.9 concussion injuries per 1000 playing hours was a relative figure which is greater than previously reported for the same cohort of players (Fuller et al., 2015; Kemp et al., 2008). It is plausible that the increase in incidence of contact-related match injuries in this cohort of players (unchanged across each of these studies (2002-2014)) is at least partially attributed to the demands of the game developing over time. Work in this area suggests there have been multiple changes to the game adapting to the high expectations of we (the public) demand of full-time athletes (Garraway et al., 2000). These standards are exemplified by the physical characteristics of the players (size and stature) and their ability to showcase above normal displays of mental toughness, speed, strength, and skill. Simultaneously, the pace of the game leading to a greater number of contact events, and the general demands of the game (relative to the duration of playing time) are at an all-time high (Fuller, Taylor, Brooks, & Kemp, 2013; Garraway et al., 2000; Quarrie & Hopkins, 2007). As a result of the increasing injury statistics, the International Rugby Board (IRB) introduced the PSCA criteria that dramatically reduced the number of concussed athletes remaining on the field of play from 58% (Kemp et al., 2008) to 15% (Fuller, Kemp, & Decq, 2014). Unfortunately, this process has not been implemented at the school-boy or amateur level, likely due to the practicality of testing procedures and the lack of medical staff available for administering the clinical procedures. A lack of proficiency to aid youth in preventing such a serious injury is in part related to the under-reporting of concussion injuries in school-boy rugby (62%) (Sye et al., 2006). Sye et al. (2006) also suggested this may be attributed to the lack of formalised definition of concussion being presented to the players or understand the term, or seriousness of the situation in the sporting context. Concussions can have devastating effects if not identified or managed accordingly, particularly in children and adolescents, as developing brains are more susceptible to the effects of concussion in comparison to an adult (Alexander, Shuttleworth-Edwards, Kidd, & Malcolm, 2015; Archbold et al., 2015). Such scarcity in this area of research lead to the initiation of the Rugby Injury Surveillance in Ulster Schools (RISUS) project; an important prospective study of youth injury surveillance in rugby (Archbold et al., 2017). In total, 825 male rugby players were recruited for the study conducted over a single season (2014/2015). Archbold et al. (2017) reported an incidence rate of 6.01 per 1000 match playing hours, similar to that of a recent review performed by Kirkwood, Parekh, Ofori-Asenso, and Pollock (2015). Even greater incidence rates were reported by Hollis et al., (2009) who studied a cohort of 3207 male non-professional rugby players over one or more playing seasons. In this study incidence rates were 7.97 per 1000 match playing hours at the amateur level (Hollis et al., 2009).

Extensive efforts regarding identification and management information (guidelines for return to play protocol) have been disseminated to sports medicine professionals and implemented in the realm of professional sports (Fuller et al., 2014). Greater efforts are required in the education of the players by the likes of coaches, trainers, medical staff, and rugby officials (Sye et al., 2006). The status of youth and amateur players' sustaining such a high number of concussion injuries and still under-reporting information on concussion warrants further study in identification and evaluation of the potentially devastating effects following a concussion.

3.1.1 Definition of Sports Related Concussion (SRC)

The 1st International Symposium on Concussion in Sport was held in Vienna, Austria in November 2001. The conference was organized by the International Ice Hockey Federation, the Federation Internationale de Football Association Medical Assessment and Research Centre, and the International Olympic Committee Medical Commission. The conference delegates and organizing bodies involved in this meeting mandated a small group of experts (labelled the Concussion in Sport Group (CISG)) to draft and release a summary and agreement position statement providing multidisciplinary consensus recommendations to improve health, safety and understanding for athletes, athletic trainers and sports medicine professionals involved in sport related concussion injury (Aubry et al., 2002). This statement included a revised definition first endorsed by the American Medical Association and the International Neurotraumatology Association over 50 years ago, which was reported to have several limitations in accounting for the common signs and symptoms of concussion and the inability to include relatively minor impact injuries that result in persistent physical and/or cognitive symptoms.

The CISG have a quadrennial meeting to examine recent information surrounding concussion in sport and if necessary revise the definition (McCrory et al., 2005; McCrory et al., 2017; McCrory et al., 2009; McCrory et al., 2013). The most recent symposium was held in Berlin, Germany (2017) where a panel of experts modified the previous CISG definition to what now follows:

"Sport related concussion is a traumatic brain injury induced by biomechanical forces. Several common features that may be utilised in clinically defining the nature of a concussive head injury include:

- ►SRC may be caused either by a direct blow to the head, face, neck or elsewhere on the body with an impulsive force transmitted to the head.
- ►SRC typically results in the rapid onset of short-lived impairment of neurological function that resolves spontaneously. However, in some cases, signs and symptoms evolve over a number of minutes to hours.

- ►SRC may result in neuropathological changes, but the acute clinical signs and symptoms largely reflect a functional disturbance rather than a structural injury and, as such, no abnormality is seen on standard structural neuroimaging studies.
- ►SRC results in a range of clinical signs and symptoms that may or may not involve loss of consciousness. Resolution of the clinical and cognitive features typically follows a sequential course. However, in some cases symptoms may be prolonged.

The clinical signs and symptoms cannot be explained by drug, alcohol, or medication use, other injuries (such as cervical injuries, peripheral vestibular dysfunction, etc.) or other comorbidities (e.g., psychological factors or coexisting medical conditions)." (McCrory et al., 2017).

The 5th International Symposium (2017) revised definition has corrected the common misconception that a loss of consciousness is not a sole or main predictor of the severity of injury. Additionally, the proposal that neuroimaging should not be the normal means of diagnosis for individuals having suffered from sports related concussion was documented. Current clinical recommendation suggests a multi-faceted approach to concussion assessment which is predominantly comprised of self-reported signs, physical symptoms, neurocognitive impairment, and balance impairment (e.g., gait unsteadiness) as no single measure has demonstrated efficacy in the monitoring of the resolution of concussion symptomology (Hobbs et al., 2016; McCrory et al., 2017).

3.1.2 Biomechanical Properties of Concussion

Understanding the proposed injury mechanism(s) of a concussive episode is important in the aid and treatment of the athlete. The biomechanical properties and pathophysiological response to mild traumatic brain injury (mTBI) in sports has been covered extensively in the literature (Giza & DiFiori, 2011; Harmon et al., 2013; King, Yang, Zhang, Hardy, & Viano, 2003; McCrory et al., 2005).

It has been demonstrated that a concussive blow causing injury to the brain is associated with three types of forces: 1) compressive forces or direct pressure; 2) inertial loading forces or indirect pressure; 3) rotational or shearing force (Harmon et al., 2013; King et al., 2003). The first is a common mechanism for concussion incidence in sport stems from a direct pressure (contact) to the head and is described as a linear (translational) accelerating - decelerating motion (Jordan, 2013). This is associated with coup and contre-coup injuries where sufficient force in the opposing direction causes the brain to strike against the inner skull (Barth, Freeman, Broshek, & Varney, 2001; El Sayed, Mota, Fraternali, & Ortiz, 2008). Typically, this type of injury in sport would occur when an athlete's head rapidly decelerates upon striking the body (or head) of an opposing player, or generating direct contact with the ground or a fixed structure (e.g., a goalpost in rugby) (Laskowitz & Grant, 2016).

The second type of forces (inertial loading) stems from indirect contact to the head which cause the head to move in the anterior-posterior / lateral direction resulting in "impulsive" forces which are transmitted to the brain (Aubry et al., 2002; Meaney & Smith, 2011). This type of pressure is commonly seen in sport and is usually a result of a large tackle or collision to the front or side of the body within rugby, resulting in a whiplash type motion (Barth et al., 2001).

The rotational or shearing force is shown to play a predominant role in the most devastating forms of mTBI (King et al., 2003; Mihalik, 2012). The mechanism of injury via rotational forces can be a result of an angular blow to the side of the face or head (temporal region) rotating the skull around the brain. The shearing rotational forces place the brain into delayed motion where the superficial and subsequently, deep tissues are compromised (Barth et al., 2001). This type of injury is commonly associated with diffuse axonal injury (El Sayed et al., 2008) and is displayed when a person is forcefully spun as a result of an impact or a direct contact is made to the head resulting in rotational acceleration of the head.

3.1.3 Neurophysiological Response to Concussion

The result of an acute traumatic force to the brain leads to a complicated and destructive disturbance initiating a neuro-metabolic cascade of events placing the brain in a state of metabolic dysfunction (Cantrill, 2011; Giza & DiFiori, 2011; Giza & Hovda, 2001; Majerske et al., 2008). This cascade can be explained by several characteristic mechanisms including a critical energy imbalance; neurotransmissions and ionic flux, neuro-inflammation, and axonal disruptions (Giza & Hovda, 2001).

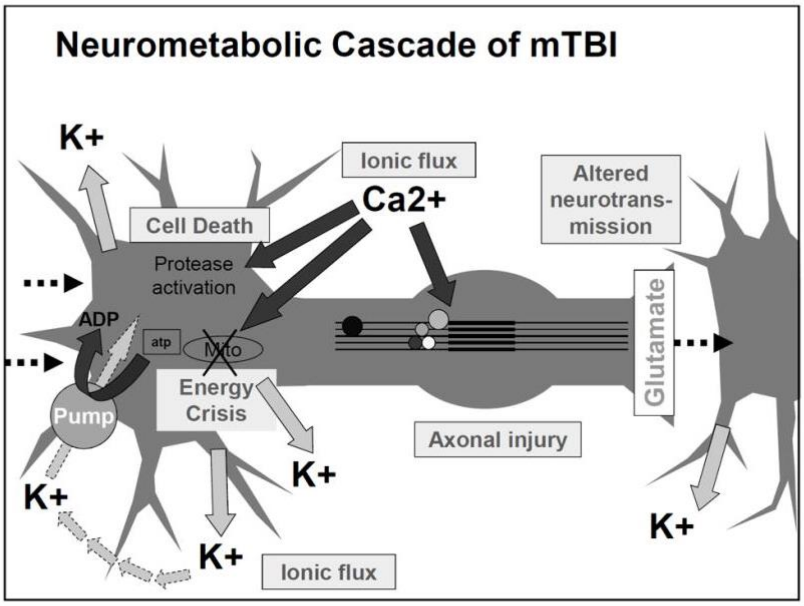

Figure 3.1. Diagram of the acute cellular biological processes occurring after concussion/mild TBI. Adapted from Giza & DiFiori (2013).

Energy imbalance crisis

According to a review written by Barkhoudarian and peers (2011), following a concussive injury, the initial damage to the neuronal membrane causes a hyper-acute widespread release of glutamate. This occurs due to mechanoporation of lipid membranes at the cellular level instigating further depolarisation, an efflux of potassium (K+), and a sodium (Na+) and calcium (*Ca*) ion influx. Depolarisation triggers ion channels, creating a vast spreading depression of neurons. The consequence of which is the activation of ATP dependant Na+/K+ pumps, which requires glucose uptake at a fast rate (see Fig. 3.1) (Seifert & Shipman, 2015). This hyper-metabolic state begins minutes-to-hours after injury and will quickly deplete intracellular energy stores and increase adenosine di-phosphate. The result is an energy crisis; a mismatch between energy supply and energy demand.

The early increase in *Ca* flux can persist longer than other ionic disturbances. A short-term solution for this is sequestration of calcium into mitochondria; however, the impairment of the mitochondrial oxidative metabolism will only worsen the problem of cellular energy imbalance (Giza & Hovda, 2001). Additionally, alterations to the intracellular redox state results in the generation of damaging free radicals, which may have extended the duration of impairment. This has a direct effect in the sporting context;

elongated vulnerability sets the stage for repeat injury. A state of impaired metabolism generally lasts up 7-10 days (Giza & Hovda, 2001; Seifert & Shipman, 2015).

Axonal Injury

While the whole brain suffers dynamic tissue damage, axons (the transmission lines of the white matter in the brain) are particularly vulnerable to deformation and disconnection during a biomechanical stretch (Smith, 2016). It was previously believed axonal disruption would invariably lead to neuronal cell death, however, in vivo animal studies have illustrated axonal disconnection occurring with shrinkage of the neuron and not cell demise (Giza & DiFiori, 2011). It can be assumed this type of damage to axons will result in abnormal functioning. More recently, Prins, Hales, Reger, Giza, & Hovda (2010 demonstrated the effect of repeated mTBI in immature rats.This is consistent with adult animal studies showing axonal injury with mTBI (Longhi et al., 2005).

Alterations in neurotransmission

Advances in neuroscience research have shown changes in ligand-gated excitatory and inhibitory neurotransmission following experimental in vivo traumatic brain injury (Giza & DiFiori, 2011; Giza & Hovda, 2001; Guerriero, Giza, & Rotenberg, 2015). These changes are dynamic and result in neuronal dysfunction and potential long-term sequelae (Guerriero et al., 2015). This imbalance is a result of alterations in glutamate receptor (N-methyl-D-aspartate (NMDA)) composition and function; reported in both the immature and mature brain (Giza & DiFiori, 2011). The functional changes in developing brains are described as interfering with plasticity development, memory, and electrophysiology. In the mature brain, NMDA receptor imbalance has been associated with calcium flux alterations, early gene activation and phosphorylation/activation of downstream signal transduction molecules (Giza & DiFiori, 2011).

Imbalances in excitatory-inhibitory balance may also be caused by γ-aminobutyric acid (GABA); the principal inhibitory neurotransmitter in the brain. The balance of glutamatergic and GABAergic tone is crucial to regular neurologic function (Guerriero et al., 2015).

Neuro-inflammatory response

Although it is certain concussion produces an inflammatory response following severe head injury (Holmin, Söderlund, Biberfeld, & Mathiesen, 1998), the inflammatory response following minor head injury, as seen in sport concussion, has been somewhat overlooked. The specific role that inflammation plays in neurodegeneration after concussion still needs to be clarified; however, the mechanism of inflammatory response has been made-clear.

Within the central nervous system, the local inflammatory response is mediated by the recruitment of neutrophils and monocytes within hours of the impact (Choe, 2016). The purpose of which is to aid the injured tissues by means of cytokine secretion and molecule signalling. Additionally, native cells, microglia and astrocytes are activated, leading to the secretion of inflammatory cytokines locally. These inflammatory cells actively create barriers between the damaged and non-damaged tissues (Choe, 2016; Loane & Byrnes, 2010). It is undeniable the injured brain produces inflammatory response (Holmin et al., 1998), but there is uncertainty behind the purpose of the inflammatory response. Suggestions of inflammation being therapeutic and aiding in neuroprotective regenerative efforts has been argued (Patterson & Holahan, 2012). On the other hand, prolonged exposure to inflammatory cytokines can be harmful to the neuroprotective response (Choe, 2016; Patterson & Holahan, 2012).

The consequence of this cascade places brain cells at risk for permanent damage and potentially death, especially if a secondary impact was to occur. To minimize incidence rates in the sporting environment, management of physical, cognitive, and vestibular changes must be recognized in the initial and subsequent assessments, and managed for a gradual return-to-play (RTP) via robust RTP protocols.

3.1.4 Post-Concussion Syndrome

Following a concussion, the various physiological, cognitive, behavioural and emotional symptoms are defined as post-concussive symptoms. The acute symptoms of concussion were reported as early as the 1600's, which were included in detail in the published workings of the "Learned Dr Read" (McCrory & Berkovic, 2001). Since this time, many authors have presented information detailing what is commonly referred to as concussion-related symptoms. Fortunately, the majority of patients who have sustained a sports-related concussion are asymptomatic within the 7-10-day period (children and professional athletes may challenge this timeframe) (Leddy, Sandhu, Sodhi, Baker, & Willer, 2012; McCrory et al., 2017). For the minority, however, the persistence of symptoms, which may linger beyond this recovery period, could represent the development of what is termed post-concussion syndrome (PCS).

PCS is diagnosed following a concussive injury when the athlete experiences debilitating symptoms beyond this acute stage (Boyd, 2014). It is usually considered when symptoms persist 90-days following mTBI with some reports of post-concussive symptoms lasting 1-year post-injury (Deb, Lyons, & Koutzoukis, 1998). Controversy surrounds PCS, with the aetiology in general disagreement and the validation of diagnostic criterion being questioned. It is known that post-concussive symptoms are non-specific and can occur in every-day life. As such, the definition is uncertain (Chafetz, 2012; King et al., 2003; Leddy et al., 2012). Nevertheless, the World Health Organization (WHO) have continued to classify PCS with a diagnosis, which is outlined in the International Classification of Diseases (10th Edition) (Graham, Rivara, Ford, & Mason, 2014).). The diagnostic criteria are as follows: A person must have a history of head trauma preceding the onset of symptoms by a period of up to 4 weeks. Patients are required to exhibit three of the six following subjective symptoms from the categories below, for a definitive diagnosis:

1) Headaches, dizziness, general malaise, excessive fatigue, or noise intolerance;
2) Irritability, emotional lability, depression, anxiety;
3) Subjective complaints of concentration or memory difficulty;
4) Insomnia;
5) Reduced tolerance to alcohol, and; 6) Preoccupation with these symptoms and fear of permanent brain damage.

In contrast, a second definition was previously put forward in the Diagnostic and Statistical Manual of Mental Disorders, 4th Edition (DSM-IV) for a post-concussion syndrome in 1994 (Brown, Fann, & Grant, 1994). This definition requires the individual to have a history of head trauma with two of the three following: loss of consciousness; post-traumatic amnesia of 12h or more, or; seizures within six months post-injury.

Evidence-based deficits in neuro-cognition are required for testing difficulties in attention, concentration, ability to shift the focus of attention, memory, and multitasking.

The problem with the WHO and DSM-IV definitions is that they are outside the parameters of PCS in a sports setting. Firstly, the DSM-IV definition requires a loss of consciousness; a symptom in which 90% of athletes who sustain a concussion do not incur (Cantu, 2007). Secondly, amnesia of minimal time (seconds) is reported to be a strong predictor of post-injury neurocognitive deficits (Collins et al., 2003). The non-specificity of symptom presence and differential diagnosis is also apparent for multiple conditions (Chafetz, 2012). The challenge for clinicians is to decide whether the clinical manifestations are a result of prolonged concussive pathophysiology or a reflection of a secondary process, e.g., premorbid clinical depression, anxiety, migraine headaches; all of which can be exacerbated by concussion (Leddy et al., 2012). Persisting symptoms can be influenced by the individual's psychological stress, social psychological factors, and personality characteristics (pre-injury personality traits). Although the initial injury is physiological, psychological factors appear to play a role in the persistence of symptoms (Chafetz, 2012). As such, the timeframe in which an athlete is diagnosed with a sport-related concussion is unknown, though it has been suggested that it is slightly less than other populations. Thus, the importance of treating and monitoring each athlete as an individual (e.g., detailing the athlete's history and progression of the number and severity of symptoms) may help understand, diagnose and differentiate between what might be resultant of an acute injury, a reflection of non-injury specific symptomology, and PCS.

3.1.5 Second-impact Syndrome (SIS) and Cumulative Head Impacts

Despite the majority of person's sustaining a single concussion recovering relatively quickly over an initial period of < 1 month, the risk for long-term problems is still conceivable. The damaging effects of repeated impacts are currently being made aware in the literature with high-risk contact sports providing researchers with the necessary means to explore the effects of multiple concussions. Evidence exists suggesting athletes who have sustained a concussion, are statistically more likely to endure another head injury (Iverson, Gaetz, Lovell, & Collins, 2004). Consequently, focus now lies on the cumulative effects of multiple concussions. Between the years 1973-2000, 26 cases of athletes who experienced initial post-concussive symptoms following a concussion, died following a second minor impact (Maroon et al., 2000). According to Throndson (1984), in 1984, Richard Saunders and Robert Harbaugh first presented a report detailing such events and coined the term second impact syndrome (SIS) (Throndson, 1984). Saunders and Harbaugh suggested these injuries have a compounding effect as opposed to concussion representing an isolated event. Their premise states that the additional impact would only add to an already compromised brain and further increase intracranial and cerebral perfusion pressures to lethal levels. In the reports of SIS, athletes had typically experienced post-concussion symptoms and subsequently returned to activity before the resolution of all symptoms and received a second brain-damaging blow to the head (Maroon et al., 2000; Quintana, 2016). Although the blow may be major or minor, the result can be catastrophic. It should be noted, conflicting criteria for diagnosing such injuries have led to scepticism over what is deemed definite SIS (Maroon et al., 2000; Quintana, 2016). Regardless of criteria, the concern of both PCS and the cumulative effects of repeated head injury exists and is reflected in the current clinical evaluation recommendation and return-to-play (RTP) protocol outlined by the CISG (McCrory et al., 2017). With athletes becoming more susceptible to prolonged effects of a concussion (e.g., persisting symptoms), serial evaluation is necessary as symptoms are known to resolve, worsen, or ebb and flow depending on additional factors (e.g., co-morbidities, cognitive status, physical exertion). For preventing SIS and other disorders, any athlete who shows signs of concussion should be thoroughly evaluated and not be allowed to return-to-play until asymptomatic.

3.1.6 Concussion Evaluation and Return-to-Play

Pitch-side Assessment

The current best-practice for immediate pitch-side care following a concussion mandates that once an athlete is diagnosed with a concussion, he/she is removed from the field of play and should not be allowed to return-to-play until cleared by a sports medicine professional. Upon removal, the athlete is immediately subjected to an in-depth battery of assessments via a multidisciplinary group of trained concussion medical professionals including physicians, physical therapists, and athletic trainers (Okonkwo, Tempel, & Maroon, 2014). The assessment includes a multi-model objective evaluation useful in differentiating concussed from non-concussed athletes, while also excluding more severe brain injury; a critical determinant of immediate decisions for the athletes (Okonkwo et al., 2014; Putukian et al., 2013). The assessment is typically a well-established and rigorously developed instrument (e.g., the Sport Concussion Assessment Tool). This contains estimates of varying clinical domains associated with concussion, e.g., red flags, signs and symptoms, cognitive and cranial nerve function, and balance (Littleton & Guskiewicz, 2013; McCrory et al., 2017). The assessment provides sports medicine professionals with an easy to follow, systematic approach to injury evaluation. According to the 5th International Conference on Concussion in Sport, the key for a pitch-side assessment is the rapid screening of a suspected SRC in the midst of competition, as opposed to gaining a precise diagnosis of head injury (McCrory et al., 2017). This is due to the majority of players not manifesting clear on-field signs and symptoms, e.g., loss of consciousness, tonic posturing, and balance impairment (Okonkwo et al., 2014). If a player sustains a significant impact and a concussion is suspected with/without these symptoms, the procedure indicates a more thorough diagnostic evaluation in a distraction-free environment (e.g., in the changing rooms). Follow-up, serially performed assessments are valued as a concussion is a developing injury with a possible delay in onset of symptoms, even if the initial evaluation is negative. However, the final decision with regards to the diagnosis and return-to-play is a medical decision based on the judgement of a physician (McCrory et al., 2017).

Recovery

Upon sustaining a concussion, individuals will experience a temporary but complex alteration in neuro-metabolic processes, which manifest by subjective somatic, cognitive, and emotional symptoms (Nelson, Janecek, & McCrea, 2013). The assessment of concussion typically involves documenting the changes in brain function via the reporting of symptoms and cognitive performance tasks. The period in which the athlete experiences concussion-related symptoms at rest is commonly referred to as the symptomatic phase. The number, severity, and duration of concussion symptoms will vary amongst athletes. This may be dependent on the type of injury and the biomechanical forces involved as well as the area(s) of the brain affected. However, individual response to recovery time and symptom resolution may also be a result of several other predictive variables including the presence of amnesia or immediate mental status change, age, sex, loss of consciousness (>1-minute), clustered symptoms, and neurocognitive impairment (Nelson et al., 2013). Until more recently, a lot of the research surrounding mild brain injury involved population samples involving community-based patients, which made it difficult to document the initial effects and natural timeframe for recovery robustly. This was primarily due to non-sport samples tending to have a lack of baseline data and co-morbidities (Nelson et al., 2013).

One of the first studies in the realm of sports concussion involved a large sample of concussed football players (n = 183) who were evaluated for self-report symptoms pre-injury, 24-hours, 5-days, and 10-days post-injury. In this study, the majority of players showed significant improvement between 24-hours and 5-days although some participants reported symptoms lasting up to 10-days (Macciocchi, Barth, Alves, Rimel, & Jane, 1996). Similarly, in 2003, Lovell and colleagues conducted research evaluating the duration of self-report symptoms and cognitive performance using a group of 64-high school athletes who had suffered a concussion. The concussed athletes were separated into two groups which were determined by immediate mental status change (retrograde amnesia, post-traumatic amnesia, or disorientation lasting >5-minutes) or no mental status change (< 5-minutes). The authors found a significant increase in symptoms from baseline to 36-hours post injury for all athletes (Lovell et al., 2003). By day 4, self-report symptoms such as a headache, dizziness, and nausea had resolved in the less severe group. Athletes with on-field mental status change (>5-minutes) reported more symptoms over the first four-days and were 5.3 times more likely to have a significant drop in performance 36-hours post-concussion. Cognitive impairment also persisted for at least 7-days after injury.

This outcome was consistent with recent findings from McCrea et al (2013) who investigated the incidence of acute and prolonged recovery from a large cohort (n = 18,531; 570 of whom were concussed) of athletes during the years 1999-2008. The athletes were assessed pre-season for baseline values then immediately and 3-hours post-injury. Follow up assessments were then re-administered at days 1, 2, 3, 5, 7, 45, and 90 days after the incident. Of the 570 concussed athletes, 90% (n = 513) were classified as having a short recovery <7-days, while 10% (n = 57) demonstrated a prolonged symptom recovery. Evidently, the typical recovery group's symptom severity was highest within the first 24-hours and started to resolve within 48-hours i.e., 2-days post-concussion. An extended recovery was associated with a loss of consciousness (<0.0001), post-traumatic amnesia ($p < 0.049$) and increased severity of symptoms ($p < 0.0001$) within the first 24-hours.

Overall, there is strong evidence that single, uncomplicated concussions, generally experience an onset of increased symptom severity in the initial 24-48 hours. A rapid resolution of symptoms in the first 7-10 days is also transparent, which is currently reflected in the consensus statement released by the CISG last year (McCrory et al., 2017). However, the challenge remains to effectively manage and reduce the risk for athletes who remain symptomatic or impaired beyond the recognised window of recovery.

Injury Classification

Throughout the literature, a large number of attempts to grade the severity of SRC; though only a few have seen some success due to a lack of reliable empirical evidence supporting them (Bodin, Yeates, & Klamar, 2012; Chafetz, 2012). In 1997, the American Academy of Neurology announced a grading system and management guideline, which encompassed many qualitative descriptors for grading the injury (Neurology, 1997). The problem with this system can be attributed to the evolving and diverse nature of the injury. Specifically, accurate identification of SRC on the day of injury is not realistic because athletes who appear to have suffered a concussion may not seem overly symptomatic in the immediate stage post-injury (e.g., symptom resolution 15 minutes post-injury) yet develop symptoms later in the day and potentially in the subsequent days following injury. Second, this classification system suggests that a brief loss of consciousness is the most prominent hallmark sign of the "*most severe*" type of concussion, a notion which has since been amended (McCrory et al., 2017). Lastly, the most obvious limitation is their lack of concern for post-concussion symptom duration. In 2001, Cantu put forward a more elaborate system which considers post-concussive symptoms and duration as key factors for classification (Cantu, 2001). The issue with Cantu's system, however, was related to the lack of clarity regarding concussions that were outside the parameters of the system (e.g., injuries resulting in amnesia less than 24 hours and 2–7 days of post-concussion symptoms) (Chafetz, 2012). In 2004, the "*simple-complex*" system was proposed by the CISG following the 2nd International Conference on Concussion in Sport. This system is based not by the characteristics of the injury, but on the number of days the athlete takes before full recovery (asymptomatic). A simple concussion was classified if the athlete recovers within ten days while a complex concussion referred to recovery times of greater than ten days (McCrory et al., 2005). In 2007, Iverson discovered that athletes who were classified as having a complex concussion presented differently than those who were identified as having sustained a simple concussion (Iverson, 2007). Complex concussions were reported to have far more symptoms and performed worse during cognitive assessments in the first 72 hours post-injury. By 2008, this system was also abandoned in favour of a focus on conservative and specific management protocol by just calling the injury a concussion; a notion put forward at the 3rd International Conference on Concussion in Sport (McCrory et al., 2009). It appears the point of this was to emphasize that although complex concussions could be classified by recovery period, they may or may not be associated with other modifying factors which may influence the investigation and account for information about the persistence or prolongation of symptoms. Thus, the current recommendations call for all athletes to be treated as individuals as determined by their clinical needs. However, it appears there is a general agreement that most concussions show symptom resolution within a short period (McCrory et al., 2017).

3.2 Concussion Assessment Tools

SRC is a common injury and can be distinguished by the vast number of signs and symptoms which resolve naturally and spontaneously over time. The typical signs and symptoms can be broadly characterised as motor (e.g., balance or gait impairments) and non-motor symptoms. Non-motor symptoms may include: physical (i.e. a headache, nausea, photosensitivity); cognitive (memory, executive function, visuospatial, or attention deficits); sensory (visual, vestibular, or proprioceptive deficits), emotional (i.e. irritability, nervousness, sadness); or sleep-related (i.e. disturbed sleeping patterns, drowsiness) (Halstead & Walter, 2010). Standardised assessment tools have been recommended by both the International Concussion in Sport Group (CISG) (McCrory et al., 2013), and the National Athletic Trainers' Association Position Statement for managing sports-related concussion (Broglio et al., 2014). There are a large number of paper-based and computerised pitch-side tools available (see Table 3.1) which help sports medical professionals by providing pertinent information to concussion identification, and also serving as a foundation for monitoring the resolution of the injury for safe return to physical activity (Graham et al., 2014).Identification of a SRC injury has typically relied on the judgment of an exercise practitioner or athletic trainer (to an accepted standard) even though the validity of such a diagnosis is yet to be recognized. Diagnostic inclusion criteria are also yet to be developed regarding which distinct areas of cerebral functioning should be incorporated into a battery of tests (Giza et al., 2013). This is reinforced by the wide variety of physical manifestations that may be exhibited following a concussive event; no two injuries result in the same alterations in cognition or symptomology (Broglio & Puetz, 2008). Current protocols for assessing concussion in sports often involve a multifactorial approach to testing with a specific focus on the domains of neuro-behavioural features, physical signs, and cognitive impairment. Using a multifactorial approach may increase the sensitivity and specificity of concussion identification (Broglio, Macciocchi, & Ferrara, 2007b; McCrory et al., 2013). However, for this review, concussion assessment tools have been categorised by their ability to identify specific areas of impairment; 1) Self-report signs and symptom scales/checklists, and; 2) neuropsychological testing.

3.2.1 Signs and Symptoms Checklists

Clinical manifestations in the form of self-report symptoms are often the primary grounds on which initial diagnosis is made (McLeod & Leach, 2012). Sports concussion and consensus statements recommended self-reported symptom checklists be incorporated as an essential part of a comprehensive evaluation process and management strategy. This is accomplished by monitoring the resolution of the injury as they are simple to measure and do not require the use of sophisticated equipment or training (Broglio & Puetz, 2008; McCrory et al., 2013). This recommendation was formerly outlined in Vienna during the 2001 first international conference on Concussion in Sport as an essential component in a graduated return-to-play (RTP) protocol (Aubry et al., 2002). Although, before this conference, it had already been acknowledged that athletes should be free from concussive symptoms before returning to play, stressing not only the importance but also the general use of symptom testing in the diagnosis and management of concussion among sporting organisations (Collins et al., 1999).

Throughout the literature, there is copious research surrounding the identification and monitoring of concussive symptoms resolution. Many checklists and self-report scales have been developed in an attempt to provide a standardised structure for sports-care professionals to objectively document concussion symptoms (Alla, Sullivan, Hale, & McCrory, 2009; Maroon et al., 2000; McCrea et al., 1998; McCrory et al., 2013; Piland, Motl, Ferrara, & Peterson, 2003). The majority of symptom scales include a combination of between 10 – 27 items, with each asking about the presence of symptoms typically reported and associated with concussion (Alla et al., 2009). The review performed by Alla et al. (2009), identified 60 relevant articles dating back to 1995 from which, six core symptom scales were identified with a further 14 published derivatives (information summarised in Table 3.1).

Table 3. 1: Summary of Assessment Tools published since 1980's.

Year Introduced	Name	No. of Items	Use of Likert Scale
1980's	Pittsburgh Steelers Post-Concussion Scale [1]	17	Yes
1998	Post-Concussion Scale (PCS) [2]	20, 21, 18	Yes
1999	Post-Concussion Symptom Assessment Questionnaire (PCSQ) [1]	10	No
2000	Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) Post-Concussion Symptom Scale (ImPACT-PCSS) [2, 3]	22, 21, 19	Yes
2001	Concussion Resolution Index post-concussion questionnaire [1, 3]	15	Yes
2001	Post-Concussion Symptom Scale [2]	20	Yes
2001	McGill Abbreviated Concussion Evaluation–Post Concussion Symptom Scale[2]	20	Yes
2003	Graded Symptom Checklist/Scale (GSC/GSS) [2]	20, 27, 18, 17	Yes
2003	Head Injury Scale (HIS) [2]	16, 9	Yes
2003	CogState-Sport Symptom Checklist [1, 2, 3]	25, 21, 14	Yes
2004	Signs and Symptoms Checklist (SSC) [1]	34	No
2004	Sport Concussion Assessment Tool (SCAT) [1]	25	Yes
2009	Concussion Symptom Inventory (CSI) [1]	12	Yes

Items = number of signs and/or symptoms used in scale. Adapted and modified from Alla et al., (2009) and King et al., (2014).

[1] Core Scales

[2] Derivatives of the Pittsburgh Steelers Post Concussion Scale

[3] Computer-based Assessment

Pittsburgh Steelers Post-Concussion Scale (derivatives below)

Developed in the late 1980's – early 1990's as a part of the Pittsburgh Steelers Concussion Management Programme, the Pittsburgh Steelers Post-Concussion Scale was one of the first acknowledged concussion symptom scales utilised in practice to monitor concussion immediately post-injury and throughout the recovery process. (Alla et al., 2009; Maroon et al., 2000). This scale contained 17-items and was the first to document symptoms severity on a 7-point Likert Scale, a measure of symptom severity which still holds weight in the majority of, and most recent concussion tools (e.g., the SCAT 5th Edition) (Echemendia et al., 2017). A large number of derivatives of this scale (*see Table 3.1*) have been developed using multiple sporting platforms (e.g., American Football and Hockey). Although, they do appear to differ in the terminology and in the number of items used on the scale (Aubry et al., 2002; Covassin et al., 2006; Guskiewicz et al., 2003; Lovell, Barth, Collins, & Echemendia, 2004; Schatz, Pardini, Lovell, Collins, & Podell, 2006).

Post-concussion symptom assessment questionnaire

The Post-Concussion Assessment Questionnaire (PCAQ) was developed by Cameron, Yunker, and Austin (1999) with the objective of presenting a protocol for the initial assessment and documentation of individuals who have sustained a mild brain injury. This protocol was to be implemented for military personnel within the Department of Physical Education at the United States Military Academy. The PCAQ comprises of three parts to assist in the monitoring of recovery. The initial assessment is a series of 10 questions to determine the presence of particular symptoms over the first 20-minutes following injury. The second part entails a take-home self-performed sheet with further questions relating to elements of concentration, memory, tiredness, mood swings and an overall feeling of normality, which were graded on a visual analogue scale to determine symptom severity (Cameron et al., 1999). The third part involved a 24-hour follow-up assessment. Additionally, participants were also instructed to return for re-assessment at 48-hour intervals until asymptomatic. This appears to be the only tool that utilizes a visual analogue scale (10-cm) for symptom severity. Still, a major limitation of the tool is that inclusion criteria were informed by previous literature, and the sensitivity and reliability of the tool were not investigated preceding its use (Cameron et al., 1999). Moreover, some of the symptoms assessed are grouped which may present unreliable data. For example, the question: do you have "intolerance of bright lights, or difficulty focusing vision" is asking about the prevalence of two separate symptoms within the same construct (Cameron et al., 1999). This may present difficulty identifying symptom resolution if a participant initially presented with both symptoms, then at 48 hours only presented with one.

Concussion Resolution Index Post-Concussion Questionnaire

The Concussion Resolution Index – Post-concussion Questionnaire was developed in 2001 as a part of the web app based computerised test battery HeadMinder (Erlanger et al., 2003; Erlanger et al., 2001). The questionnaire contains a 15-item checklist asking about the presence and severity of commonly reported signs and symptoms. See section *3.2.3 HeadMinder: Concussion Resolution Index* for a more thorough detailing of the tool.

Signs and Symptoms Checklist

The Signs and Symptoms Checklist (SSC) was originally presented in 2004 by Pellman and colleagues who published a series of articles surrounding concussion injuries in professional American football (Pellman, Lovell, Viano, Casson, & Tucker, 2004; Pellman,, et al., 2004; Pellman, Viano, Casson, Arfken, & Powell, 2004; Pellman, Viano, Casson, Tucker, et al., 2004). The SSC was founded by a group of the mild traumatic brain injury committee consisting of medical and research experts from the fields of sports neurology and epidemiology, sports neuropsychology, mild traumatic brain injury and basic scientific research with the intention to bring uniformity to medical personnel involved in the NFL. Concussion data was collected prospectively during a 6-year period (1996-2001) from 650 players in games and practices as reported by 30 National Football League Teams. The data examined the epidemiological features of concussion including the frequency of head injury as well as the clinical symptoms associated with concussion. The SSC included a 34-item symptom checklist from common signs and symptoms that were grouped into six categories: 1) general symptoms; 2) somatic complaints; 3) cranial nerve findings; 4) cognitive abnormalities; 5) memory problems, and; 6) unconsciousness. The form was purposely large with the intention to capture all of the possible signs and symptoms consistent with previous medical literature which included both self-report and assessed symptomology as reported by a trained professional (Pellman, Viano, Casson, Tucker, et al., 2004). Due to the volume of items on the checklist, and the requirement of sports personnel to administer (in-part), performing the assessment may be time-consuming. The SSC was used for initial evaluation and subsequent follow up assessments.

Sport Concussion Assessment Tool (SCAT)

Following the development of the Standardized Assessment of Concussion (SAC) in 1997 (McCrea, Kelly, Kluge, Ackley, & Randolph, 1997), the need for a comprehensive concussion screening assessment that could be adopted by multiple sporting codes and organizations was identified (Yengo-Kahn et al., 2016). Consequently, a panel of multidisciplinary experts formed the Concussion in Sport Group (CISG), which led to the introduction of the Sport Concussion Assessment Tool (SCAT) (Aubry et al., 2002). The first iteration of the SCAT used a combination of the previously used SAC, a standardized symptom scale (Post-Concussion Symptom Scale [PCSS], identified sport specific questions (in the form of modified Maddocks' questions (Maddocks et al., 1995), and a guideline for return to play in a stepwise fashion (McCrory et al., 2005). As a part of the Consensus Statement on Concussion Summary Agreement from CISG, the SCAT was published with the intention to serve as an educational tool and a standardized side-line assessment for acute evaluation and concussion management (Aubry et al., 2002; Graham et al., 2014). The SCAT contained an 18-tem scale for the initial acute assessment with a further 7-items assessed at follow up visit with completion time running approximately 15-20 minutes (Alla et al., 2009; Aubry et al., 2002; Dziemianowicz et al., 2012). It establishes high face validity with the items being obtained by a panel of experts and published sources (Alla et al., 2009). The SCAT was refined in 2008 (McCrory et al., 2009) and 2012 (McCrory et al., 2013) culminating in new editions (SCAT 2 & 3). The latest review of current literature led to the development of the SCAT 5 (see Appendix D), the newest concussion assessment tool to date (Echemendia et al., 2017). The SCAT 5 made no new additions to the SCAT 3 with regards to symptom evaluation, with both containing a 22-item checklist as a part of its multi-faceted assessment. The SCAT 5 is endorsed by major sporting entities including FIFA, World Rugby and the International Olympic Committee. The SCAT reflects the most current knowledge about concussions with the ability to assess multiple areas of cognitive functions which are potentially affected by concussion. It demonstrates clinical utility when assisting in diagnosis immediately post injury and differentiating concussed from non-concussed athletes when using either intra-individual or normative baseline/post injury comparisons (Echemendia et al., 2017).

Glasgow Coma Scale

The Glasgow Coma Scale, originally developed in 1974, is a symptom checklist that objectively measures responses of eye opening, motor, and verbal that can be administered to athletes on the field of play (Graham et al., 2014). As a current component of the SCAT, the GCS primarily measures an athlete's level of consciousness and to rule out severe brain injury (Dziemianowicz et al., 2012; McCrory et al., 2013). The scale has previously been recognized as a predictor of injury severity following concussion; however, caution must be used when interpreting this scale as a patient with mild concussion may still present with a high (good) score on the scale (McCrory et al., 2013)). It was for this reason that the Glasgow Coma Scale was removed from the Signs and Symptoms Checklist in 1999, and data pertaining to loss of consciousness was added (Pellman, Powell, et al., 2004). An individual does not have to lose consciousness to be concussed; hence the efficacy of assessing level of consciousness may be questioned.

Concussion Symptom Inventory (CSI)

Although many of the identified checklists have demonstrated sensitivity for detecting symptoms associated with concussion (Erlanger et al., 2001; Schatz et al., 2006), they are not empirically derived, rather, they are developed through clinician experience (Alla et al., 2009; Eckner & Kutcher, 2010; McLeod & Leach, 2012). The Concussion Symptom Inventory (CSI) however, was resultant of a multi-study project analysis for the purpose of deriving the most sensitive and efficient scale for the detection and tracking of self-report signs and symptoms (Randolph et al., 2009). The data for the study was collected from three separate studies using symptom checklists, the Concussion Prevention Initiative (CPI), the NCAA Concussion Study, and the Side-line = the Project Side-line between the years 2000-2003. In total, 27-items were tabled and graded on a 7-point Likert scale. The data pool was taken from a total of 16,350 high school and collegiate based athletes; 641 of which suffered a concussion. Information of concussive symptoms was gathered immediately post injury, post-game (approximately 3-hours) and subsequently on days 1, 3, and 5 post-injury (Randolph et al., 2009).

In 2009, Randolph et al., performed an analysis of the three checklists. The purpose was to eliminate any symptoms deemed insensitive for detecting concussion. The criteria for elimination was an effect size of <0.3 on less than two-of-five injury assessment points. The CSI retained 12-items of the 27-item list for inclusion: headache; nausea; balance/dizziness; fatigue; drowsiness; feeling slowed down; in a fog; difficulty concentrating; difficulty remembering; blurred vision; sensitivity to light; and sensitivity to noise. To ensure sensitivity and specificity was not lost through the elimination of 15/27 items, the authors conducted a received-operating characteristic curve (ROC). The ROC analysis revealed a near identical sensitivity and specificity from day 1 – 5 (95% C.I.) post-concussive injury. Despite the CSI development as a succinct and precise symptom checklist, limited efforts have been placed on applying the scale in published research. Perhaps the dominance of the SCAT being used by most major sporting entities as a preferred choice could explain the lack of prospective application in concussion-based research in spite of the advantage of a reduced administration time (Eckner & Kutcher, 2010) and empirical evidence of its sensitivity.

Pros and Cons

The global development and availability of self-report signs and symptom scales has been driven by the recommendation of International consensus statements and their use in clinical and sporting situations (Broglio et al., 2014; McCrory et al., 2017). The efficacy of these scales appears to be synonymous with diagnosis and serially used throughout the recovery process for identifying common symptoms associated with concussion. Although the appearance of symptoms is a clear indication of concussion, the use of stand-alone symptom scales warrants caution. Rather dissimilar to other assessment techniques commonly used in SRC (e.g., neuropsychological testing), symptom presence and severity are determined by subjective reporting. The subjectivity of symptom presence could lead to an inaccurate reflection of the athlete's symptomology, which could potentially hinder its usefulness for assisting in diagnosis or recovery (Dziemianowicz et al., 2012; Guskiewicz et al., 2003). Self-report assessment may lead to the deliberate underreporting of symptoms as a means of avoiding removal from the field of play or in an effort to hasten the return-to-play protocol (Van Kampen, Lovell, Pardini, Collins, & Fu, 2006). McCrea, Hammeke, Olsen, Leo, and Guskiewicz (2004) also suggested that under-reporting of SRC may be due to a lack of knowledge (e.g., not being aware of the injury's signs and symptoms). By following position statement recommendations, the utilisation of self-report signs and symptoms checklists, in conjunction with various neuropsychological assessment criteria will help prevent, or at least minimise the obvious limitation of false subjective reporting.

Most of the listed scales are comprehensive and have a large number of items ranging from 10-27. Inter-scale variability is noted regarding the inclusion of symptoms (number and type) although similarity has been demonstrated throughout (Table 3.2). In total, 41 signs and symptoms have been presented in the scales identified and listed on Table 3.1. Table 3.2 presents the signs and symptoms, and the occurrence in each of the scales aforementioned. Four signs and symptoms included in the Signs and Symptoms checklist (syncope, vertigo, pupil size, and pupil response) were excluded from the Table as the author believes greater clinical evaluation was necessary. Only five items were used consistently across all six scales: headache, nausea/vomiting, sensitivity to light, difficulty concentrating and fatigue/low energy. Other repeating items (5 of the 6 scales) were difficulty remembering, trouble falling asleep/sleep disturbance, irritability, and dizziness. Loss of consciousness was also evaluated in four of the six scales. With such a high number of symptoms assessed, the burden of a high completion time is evident, especially when combined with assessment of other areas of concussion (i.e., the SCAT). It is also worth noting that while many symptom scales and checklists exist, there is no consensus upon what is the "*gold standard*" assessment tool. Although, the SCAT does appear to be the most comprehensive and multidimensional tool.

Limited attention has been placed on the significance of empirically derived scales despite such variability in post-concussive symptom presentation (Macciocchi, Barth, & Littlefield, 1998). Of recent note, the shortened version of the CSI (12-item) is a current representation of a concise and sensitive empirically derived symptom scale, which has the added benefit of reduced time to complete. An interesting finding saw none of the items included in the CSI were assessed in less than three scales, providing face validity to the signs and symptoms assessed; the subjective degree to which the assessment appears effective in terms of its stated aims. However, the problem remains that development of symptom scales and derivatives have overtaken the need to investigate psychometric properties. It appears many of the abovementioned symptom scales have more or less "evolved" as opposed to methodological development through scientific scrutiny, and therefore do not meet the criteria classically associated with the term 'scale' (McLeod & Leach, 2012). According to Alla and colleagues (2009), scales require properties such as symptom selection, repeatability, sensitivity, validity, and specificity to be scientifically and systematically established. Supporting evidence for the development, reliability, and validity of empirically derived scales is essential and only then can strong inferences based upon the scores be made.

Table 3.2: Signs and symptoms assessed in common self-report checklists for concussion identification.

	Signs and Symptoms Checklist	SCAT 5	Pittsburgh Steelers PCS	CRI-PCQ	PCA-Q	CSI
Headache	✓	✓	✓	✓	✓	✓
Nausea or vomiting	✓	✓	✓	✓	✓	✓
Sensitivity to light	✓	✓	✓	✓	✓	✓
Difficulty concentrating	✓	✓	✓	✓	✓	✓
Fatigue or low energy	✓	✓	✓	✓	✓	✓
Difficulty remembering		✓	✓	✓	✓	✓
Trouble falling asleep/disturbances	✓	✓	✓	✓	✓	
Irritability	✓	✓	✓	✓	✓	
Dizziness	✓	✓		✓	✓	✓
Balance problems	✓	✓	✓	✓		
Blurred vision	✓	✓			✓	✓
Sadness or depression	✓	✓	✓	✓		
Loss of consciousness	✓	✓		✓	✓	
Sensitivity to noise		✓			✓	✓
Feeling slowed down		✓	✓			✓
Feeling like "in a fog"		✓	✓			✓
Nervous or anxious		✓	✓	✓		
Drowsiness		✓	✓			✓
Neck Pain	✓	✓	✓			
Confusion		✓		✓		
Tinnitus	✓				✓	
Anxiety	✓				✓	
Back pain	✓					
"Don't feel right"		✓				
"Pressure in head"		✓				
More emotional		✓				
Seizures	✓					
Diplopia	✓					
Nystagmus	✓					
Hearing loss	✓					
Personality changes	✓					

CRI = Concussion Resolution Index; CSI = Concussion Symptom Inventory; PCA-Q = Post-Concussion Assessment Questionnaire; PCS = Post-Concussion Scale; SCAT5 = Sports Concussion Assessment Tool version five (Cameron et al., 1999; Echemendia et al., 2017; Erlanger et al., 2001; Lovell et al., 2006; Maroon et al., 2000; Randolph et al., 2009).

3.2.2 Neuropsychological Assessment

Neuropsychology involves the study of brain-behaviour interactions, specifically in the ways of how neural structures and activity are manifested through physical behaviour and areas of cognition (Chafetz, 2012). Historically, neuropsychological assessments have been used for observing and documenting the effects of mild traumatic brain injury on various cognitive domains (e.g., attention, visual/verbal memory, information processing speed, continuous learning) (Guskiewicz et al., 2004). Only in recent years has neuropsychology seen a rapid emergence as a speciality area of practice in sports-related concussion. This was first introduced in the late 1980's in the groundbreaking work of Jeffrey Barth who studied the nature and outcomes of concussion in more than 2000 collegiate athletes from 10 different universities using the Sports as a Laboratory Assessment Model (Barth et al., 1989; Graham et al., 2014). The idea influenced Lovell (1999) to construct a similar programme with the Pittsburgh Steelers, which rapidly lead to neuropsychological programmes in both the National Football League and the National Hockey League (Chafetz, 2012). Before Barth et al. (1989) and their landmark study, neurologic and neurocognitive alterations following concussion were considered insignificant (Johnson, Kegel, & Collins, 2011). The speciality practice has since been labelled the 'cornerstone' of concussion management by the Vienna Concussion in Sport Group (CISG) (Aubry et al., 2002; Harmon et al., 2013; Johnson et al., 2011). This recommendation can be attributed to several reasons including 1) neuropsychological assessment, as a part of a multidimensional approach, provides the greatest amount of information regarding the heterogeneous nature of sports-related concussion (Grindel, Lovell, & Collins, 2001); 2) Standalone measures are insufficient for detection of the full sequelae following injury i.e., a reliance on self-report signs and symptoms alone is inadequate and is likely to lead to a significant number of misdiagnoses (Van Kampen et al., 2006), and is accentuated by the under-reporting of symptoms being documented at various levels of sports competition (Sye et al., 2006; Williamson & Goodman, 2006), and; 3) a disconnect between the timeframe of symptom resolution and neurocognitive recovery; an athlete may experience prominent symptoms in one domain and subtle in another (Broglio & Puetz, 2008; Echemendia et al., 2013). Although there are no exact indications of which specific neuropsychological assessments are most valuable in SRC evaluation, the role of neuropsychological assessments as part of a multidimensional approach allows for integrative outcome measures of various cognitive domains. This will have greater potential for recognising deficits in cognition than any other single approach (Guskiewicz et al., 2004).

The role of the Neuropsychologist

Neuropsychological assessments help physicians diagnose injury; however, they are also useful in the monitoring of recovery once a diagnosis of concussion has been made. During the pre-season, the role of the neuropsychologist is to set a benchmark for each individual player by performing baseline assessment. This enables the neuropsychologist to gauge the status of the athlete by aiding in the understanding of the subtle effects of a concussive injury on cerebral functioning, should it occur. It should be noted in some settings, neuropsychologists only become involved once an athlete has sustained an injury, and not for baseline testing (Echemendia et al., 2013). This is largely based on the CISG (2017) panel recommendation that suggests baseline neuropsychological testing is not felt to be required as a mandatory aspect of every assessment, despite its helpfulness in providing useful information to the overall interpretation of these tests (McCrory et al., 2017). Further discussion on this topic is provided in detail below.

The role and value of baseline assessments

Succeeding the model outlined by Barth et al (1989), physicians have used two different methods for concussion data interpretation. The first involves the comparison with individual baseline assessment data. The second involves a comparison to normative data. Theoretically, individual baseline assessment is advantageous for numerous reasons. Firstly, individuals vary markedly in ability concerning test of cerebral functioning. Secondly, without knowledge obtained by appropriate base-line testing (before a concussion), the difficulty lies in assessing whether deficits in cognition are related to the effects of concussion or previous unrelated reasons. Obtaining appropriate information regarding histories of previous concussions (e.g., severity and number) can then be included in pre-season testing (Guskiewicz et al., 2004). Despite this, research surrounding sports concussion continues to hold much controversy. One study demonstrated the utility of a computerised neuropsychological tool in the absence of baseline data (Schmidt, Register-Mihalik, Mihalik, Kerr, & Guskiewicz, 2012). This included large amounts of data as part of an ongoing concussion surveillance and management programme with 1060 collegiate student-athletes. The authors concluded that using normative data instead of individualised baseline measures is an appropriate and feasible evaluative approach to SRC. This was consistent with findings from a similar study performed by Echemendia et al. (2012). However, several methodological flaws have been pointed out. Firstly, both studies reported small rates of decline from baseline to follow up assessment (2-24%). For optimally deciphering the usefulness of the baseline method, a larger rate of true impairment (concussion-related) is warranted. Furthermore, the criteria used in the analysis of baseline and normative methods may have resulted in the normative method having increased sensitivity to detecting cognitive impairment. For example, of the 258 concussed athletes involved in Schmidt's research, a small number performed poorly in baseline measures, resulting in scores well above the normative mean. This resulted in 18 diagnosed concussions in going undetected (Schmidt et al., 2012).

Having recognised the limitations of previous research, Louey and colleagues (2014) further investigated the sensitivity and specificity of CogSport. The authors used a previously validated baseline method (Collie, Maruff, Darby, & McStephen, 2003), vs. normative methods in 260 healthy asymptomatic athletes, and 29 recently concussed athletes participating in the Australian Rules Football or Rugby Football Union club competitions. The results from this study suggest the baseline method has both higher sensitivity and specificity that the normative method using the CogSport/Axon test battery (Louey et al., 2014). In fact, 28% of the concussed athletes in this study whom were recognised as impaired using the baseline method, were classified as unimpaired using the normative method (Louey et al., 2014).

In conjunction with the recommendations from the consensus statement of the CISG (McCrory et al., 2017), these findings confirm the superiority in the sensitivity of the baseline method in comparison to the normative method. It is important to mention, however, the number of factors that can potentially affect baseline performance. Firstly, despite the favourable utility of CNT, caution must be taken due to the impact of learned variance from the baseline assessment. Using the CNT software CogSport, Straume-Naesheim, Andersen, and Bahr (2005) baseline tested 289 professional footballers and interesting observed significant improvements in test scores with two consecutive tests performed on the same day. Similarly, Kaminski, Groff, & Glutting, (2009) demonstrated that reliability of test results on the Automated Neuropsychological Assessment Metrics system was evident after performing the test over two consecutive time periods. Thus, to achieve reliable data for further comparative means familiarity with the testing tool is required, with the initial test being discarded due to unfamiliarity.

Additionally, mental health disorders such as depression and anxiety, as well as excessive stress (Covassin, Elbin III, Larson, & Kontos, 2012), distractions of grouped testing environment (e.g., typing, talking, movement) (Moser, Schatz, Neidzwski, & Ott, 2011), and sex (Schmidt et al., 2012), are recognised as performance-affecting factors in baseline testing. Dehydration (Neylan et al., 2010), and a lack of sleep or fatigue (McClure, Zuckerman, Kutscher, Gregory, & Solomon, 2014; Neylan et al., 2010), can also impair cognitive functioning and subsequently, test performance. Moreover, athletes "sandbagging" their performance, leaving an invalid baseline assessment, is a potential problem noted in the literature (Nelson, Pfaller, Rein, & McCrea, 2015; Schatz & Glatts, 2013). Therefore, a certain level of cognitive and behavioural engagement in the performance is necessary (Bigler, 2014).

A comprehensive test battery on every athlete can be very time-intensive and costly. All factors should be accounted for when developing test batteries as invalid baseline test results is not uncommon throughout the literature (Schatz et al., 2014). Nonetheless, due to the complex nature and different pathological possibilities in SRC, the collection of objective pre- and post-concussion data appears to be the more accurate and optimal approach for detection and monitoring recovery.

3.2.3 Computerized Neuropsychological Test (CNT) Batteries

Traditionally, comprehensive neuropsychological assessments for athletes involved pen and pencil, and face-to-face administration. Such assessments contain established measures with evidence of psychometric competence stemming from large amounts of normative data (Arrieux, Cole, & Ahrens, 2017). This method of implementation has been used for multiple sports and sporting levels (Barth et al., 1989; Chafetz, 2012; Collins, Stump, & Lovell, 2004; Lovell & Collins, 1998). However, some practical inadequacies involving feasibility, expense, time, administration, and interpretation associated with pen-and-pencil approach paved the way for an alternative; computerised neuropsychological testing (CNT) (Collie, Maruff, McStephen, & Darby, 2003). Recently, CNT's have become increasingly popular in the sporting context with several test batteries specially designed for wide-spread commercial use; however, many of these tools have not been sufficiently or consistently established and are not psychometrically sound. According to DeVon and colleagues (2007, p. 155) "*The foundation of all research designs is the use of instruments that are psychometrically sound*". The most important aspects of which include reliability, validity, and sensitivity. Ensuring the instrument is reliable and sensitive is a prerequisite to instrument development, which assures the integrity of the research outcomes. Of the current CNT on the market, three main test batteries were developed; all of which have shown promise in these areas: 1) the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT); 2) CogSport, and; 3) HeadMinder. A short review of each is presented below.

Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT)

The Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT; ImPACT Applications, Inc., Pittsburgh, PA) is an extensive computer-administered neurocognitive test battery which was originally developed by Lovell and colleagues. ImPACT is a Windows-based programme which yields specific measures for areas of cognitive function, including attention, verbal memory, visual memory, reaction time, and information processing speed. The test battery can be administered using a microcomputer which minimises supervision. The reaction times are measured to 0.001 seconds to account for fatigue and its effects on information processing speed. Each time the test is conducted, the presented stimulus is infinitely randomised as a preventative control for typical practice effects associated with pen-and-pencil testing (Majerske et al., 2008; Maroon et al., 2000). The programme also consists of a concussion history questionnaire and a 22-item self-report signs and symptoms checklist (Post-concussion Symptom Scale (PCSS)). The ImPACT has previously demonstrated validity and reliability for the assessment of concussion (Iverson, Lovell, & Collins, 2003, 2005; Schatz et al., 2006). Numerous alternate studies have also made efforts to examine the sensitivity of the test battery (Broglio, Macciocchi, & Ferrara, 2007a; Iverson, Gaetz, Lovell, & Collins, 2004; Tsushima, Oshiro, & Zimbra, 2008). It appears ImPACT has been researched more thoroughly in sports concussion than any other traditional or computerised assessment battery.

CogSport

CogSport (CogState Ltd, 1999, Melbourne, Australia) is a neuro-cognitive computerized test battery developed by Alex Collie and colleagues for the purpose monitoring recovery from a concussion and assisting sports medicine practitioners in return-to-play decisions (Iverson, Brooks, Collins, & Lovell, 2006; Makdissi et al., 2001).

CogSport test battery has been used to examine the effects of concussion in many studies (Collie, McCrory, & Makdissi, 2006; Falleti, Maruff, Collie, & Darby, 2006; Louey et al., 2014; Makdissi et al., 2001). The test battery consists of eight "*card game*" based tests to create a game-like atmosphere and encourage motivation for performing the assessment. CogSport measures multiple areas of cognition using the baseline approach (pre-and-post injury) to interpret the extent of impairment. Of the eight test battery components, four have been identified as the most useful in detecting and managing SRC: simple reaction time; complex reaction time; working memory and learning. The test measures response-reaction times and data accuracy, and takes approximately 15-20 minutes to complete. The CogState sports symptom checklist was also incorporated as a part of the computerised programme, which was a late derivative from the McGill Acute Concussion Evaluation Post-Concussion Symptom Scale. Later versions of the programme (V.5.6 and V.3.3) instead contained the Sport Concussion Assessment Tool – Post-concussion Symptom Scale (SCAT-PCSS) which included a 25-item checklist (Alla et al., 2009). The battery is a freeware internet-based product and runs under Windows and Macintosh Operating Systems. CogSport provides user-friendly and unlimited online tech support with locally stored data (on the user's computer) or remotely on CogState's server. Optional services also include report generation (customised) and assistance in interpretation of results (Schatz & Zillmer, 2003).

HeadMinder: Concussion Resolution Index

The Concussion Resolution Index (CRI: HeadMinder Inc, New York, NY), is an extensive neurocognitive test battery developed by Erlanger and colleagues in 2001 (Erlanger et al., 2001). The CRI is an independent, online (web-based) programme consisting of six-sub-test modules designed to objectively measure cognitive constructs associated with SRC, such as 1) simple reaction time; 2) cued reaction time; 3 & 4) visual recognition; 5) animal decoding, and; 6) symbol scanning (Erlanger et al., 2003). The CRI sub-tests form three indices of psychomotor, speed index, and simple reaction time and have been proven sensitive to the effects following concussion with reliable change scores upon retest (Erlanger et al., 2001). Additional information collected includes demographic, medical history (concussion history included), and a 15-item signs and symptoms checklist; the Concussion Resolution Index Post-Concussion Questionnaire. The tests are measured online, and the test administrator or person who is responsible for understanding the results then feeds the information to the athletes. The administration time is approximately 20-25 minutes to complete. This reflects the general concern surrounding administration time and medical staff requirements; requiring a person to interpret suggests limitations in the number and frequency of possible serial assessment due to limited resources. Reports of its development and psychometric properties are available in greater detail (Broglio, Macciocchi, & Ferrara, 2007; Erlanger et al., 2003; Erlanger et al., 2001).

3.2.3.1 Reliability

The utility of the CogSport, ImPACT, and the CRI for diagnosing, evaluating, and monitoring change has been a topic of controversy throughout the literature. At the core of this lies the test-retest reliability of these measures. Put simply, test-retest refers to the consistency of a given test score; however, it also pertains to the clinical inferences derived from a test. This is explained by Berchtold (2016), as having two different notions when considering the stability of instrument measurement: 1) test agreement, and; 2) test-retest reliability. Test agreement refers to the ability of an instrument to produce the same results for the same participants when repeated under the same conditions on separate occasions. Test-retest reliability considers general reliability based on correlation coefficients; a measurement is pertaining to the level of association between two sets of measures. Reliability coefficients usually sit somewhere between perfectly reliable ($r = 1.00$) and unreliable ($r = 0.00$). This is referring to the linearity of the relationship between the two sets of measures, not the equality of values and is applied in different contexts, to diverse groups. This is a common misconception that dominates the notion of repeatability. Sports concussion research is rife with concern surrounding the instability and reproducibility of current widespread tools (Resch et al., 2013). This concern is founded on various problems associated with practice effects, regression to the mean, and test-retest reliability using the baseline model for repeatability (Erlanger et al., 2003). Reports of test-retest reliability of CNT's such as ImPACT, CRI, CogSport test batteries are plentiful (Broglio, Ferrara, Macciocchi, Baumgartner, & Elliott, 2007; Collie et al., 2003; Elbin, Schatz, & Covassin, 2011; Erlanger et al., 2003; Miller, Adamson, Pink, & Sweet, 2007; Schatz, 2010; Schatz & Ferris, 2013).

The reliability of CogSport was first reported by Collie et al (2003) in a two-part study. The authors determined the reliability of the test battery by calculating intra-class correlation coefficients on the serial data collected at baseline and a 7-day follow up trial from 60 healthy volunteers. The results of CogSport speed indices demonstrate high to very high ICC coefficients (0.69 – 0.90) at the re-test intervals of 1-hour and 1-week, whereas CogSport accuracy indices displayed greater variability and lower ICC coefficients (0.08 – 0.51).

Around the same time, Erlanger and colleagues (2003) also documented the test-retest reliability for the concussion assessment tool: Concussion Resolution Index (CRI), of 414 participants. The authors reported test-retest reliabilities for processing speed (0.82), simple reaction time (0.70) and complex reaction time (0.68). No significant change was found from the first to the second test instance for simple or complex reaction time. However, a significant increase was identified for processing speed ($p = <0.01$).

Test-retest reliability for ImPACT was first reported over a 7-day period by Iverson, Lovell, and Collins (2003). The authors examined the test-retest reliability for 56 healthy young adults. Not unlike previous results using CogSport, the authors found good correlations (Pearson's Correlation Coefficient) between the initial assessment and the 7-day follow-up (0.65 – 0.89), except for the processing speed composite which was identified as significantly different ($p = <0.003$) in 38 of the 56 participants performing better at follow-up. Several studies between 2007 – 2013 have also reported test-retest reliability of ImPACT scores over varied elapsed time intervals of four-weeks (Schatz & Ferris, 2013); 45-days (Broglio, Ferrara, et al., 2007); 4-months (Miller et al., 2007); 1-year (Elbin et al., 2011), and 2-years (Schatz, 2010). Collectively, and contrary to Iverson's findings, the processing speed composite displayed the least instability across all four of these studies (Schatz & Ferris, 2013). When comparing Pearson's correlations (r) and Intraclass Correlation Coefficients (ICC) across retest intervals of 7-days, 4-months, 1-year and 2-year studies, values tend to show a gradual linear decline as function of time between assessment intervals for verbal memory ($r = 0.70 – 0.30$/ ICC

=0.79 – 0. 46), visual motor speed (r = 0.86 – 0.60 / ICC = 0.88 – 0.74), and reaction time (r = 0.79 – 0.52 / ICC = 0.77-0.68), The exception to this was visual memory, which displayed a rapid decline from 7 (r =0.67) to 30 days (r = 0.43) before improvement at the 1-and-2-year retest intervals (0.49-0.55) (Schatz & Ferris, 2013). It is possible the variability of these values could reflect the varying methods among studies. It should also be noted that in Broglio's study of ImPACT, CRI, and CogSport, ICC at the 45-day interval, values were significantly lower than other reports (0.23 – 0.39) for all four ImPACT composites and were not included in the findings presented. This variability of outcome places questions surrounding the quality of methods used, specifically, in the context of completing multiple test batteries which are comprised of similar assessments. Except for Broglio's study, the only correlation which did not reach what was identified as the acceptable threshold (0.60) was the visual memory composites.

Although the concept of perfect reliability and agreement is more theoretical than realistic in most cases, it should still be the objective. It could be argued that lowering these expectations can only lead to unsatisfactory tools, misinformation, and potential for misdiagnosis, or misclassification of injury. The physician needs to be aware of potential errors such as false-positives or false-negatives, which may lead to unnecessary conservative management of injury, or inappropriate and premature return-to-play decisions. Such variability during a serial assessment of cognitive tasks only enhances the importance of face-to-face examination by a licensed physician (Resch et al., 2013).

Of the CNT's mentioned in the review, it appears that ImPACT has been subjected to rigorous scientific research, yet still demonstrates large instability. Still, concluding that the values found in these studies are an indicator of good reliability only further encourages the misconception that the widespread CNT's do in-fact present reliable information. This suggests more research is needed with bigger sample sizes, population samples, genders, and age grouped participants.

3.2.3.2 Sensitivity

In the early stages of sport concussion management, grading scales were used to identify injured athletes by classifying them by injury severity. Similarly, decisions surrounding return-to-play were based on predetermined guidelines, each alluding to different recommendations for diagnosis and management decisions. On a large scale, it could be argued beneficial; however, the subjectivity of diagnosis is based solely on the physician's clinical experience. Therein lay the problem. At the time, with the self-reporting nature of symptoms and the clear lack of cognitive assessment, it was seemingly impossible to guarantee the injured athlete to be entirely free from cognitive impairment and consistent with pre-injury cognitive status. With Barth et al (1989) introducing the first research driven derived scales with a baseline-to-post-injury approach and the inclusion of neurocognitive assessment, accountability for inter-individual variations in symptom presence, severity, and duration throughout the course of recovery became possible. This idea refers to the sensitivity of the concussion tool i.e., the probability that a test result will be negative when a concussion is not present and be positive when a concussion is present. This is crucial when trying to reduce injury risk and potentially reduce further injury by minimising premature return-to-play. It will also ensure a concussed individual is advised to seek medical attention when needed and not misdiagnosed. The sensitivity of existing concussion assessment tools has been demonstrated throughout the literature (Broglio, Macciocchi, et al., 2007b; Erlanger et al., 2001; Schatz et al., 2006).

In 2001, Erlanger and peers field tested the sensitivity of a new (at the time) web-based neuropsychological concussion assessment tool; the CRI. The authors obtained baseline and post-injury (every 1-2 days until asymptomatic) data of 834 high school athletes; 26 of whom sustained a concussion and were studied. The results indicated a total of 23 (88%) athletes were correctly diagnosed post-trauma. Of the 26 concussed athletes, 20 of them displayed self-report symptoms, 18 (69%) displayed impairment in at least one neurocognitive test, and 11 (42%) athletes had more than one significant cognitive finding at the initial follow-up assessment. Interestingly only 15 (58%) of the athletes manifested in both symptom and cognitive decline. This illustrates the importance of including neurocognitive measure in a test battery for increasing diagnostic ability.

In 2006, Schatz demonstrated the diagnostic utility of ImPACT by observing 72 concussed and 66 non-concussed athletes from multiple sports (Schatz et al., 2006). The concussed athletes were required to have sustained a concussion within 72-hours of participating in the study. By collecting the baseline and post-concussion data, the sensitivity and specificity of the ImPACT could be determined by differentiating alterations in cognitive functioning from concussed vs. non-concussed individuals. Using the ImPACT symptom score, the sensitivity was 81.9% and the specificity was 89.4%

To further examine the sensitivity of ImPACT and CRI, Broglio (2007) examined the sensitivity of both the CRI and the ImPACT as a part of an ongoing study between the years 1998-2005. During this time 75 athletes who sustained a concussion were included in the data analysis, however, only 28 were assessed for both symptom duration and severity post-injury and at follow-up, 24 hours later. At follow-up ImPACT and CRI demonstrated deficits in cognitive and/or symptomatic variables of 79.2% and 78.6%, respectively. Subsequently, the results indicated that ImPACT was 91.7% sensitive to effects of concussion while CRI was 89.3%.

Given that the standard techniques of neurological examinations (neuroimaging and electrophysiological techniques) are notorious for poor detection of concussions, accuracy and sensitivity for detecting sports related concussion can be difficult (Schatz et al., 2006). At least for healthy individuals, both ImPACT and CRI appear to be sensitive for detecting SRC. However, of the studies mentioned, between 12-18% of concussed athletes were not diagnosed correctly by the CNT's currently available on the market. Statistically, it is not very significant; however, this could have serious implications, especially at high school and collegiate level sport, where there are limited sports medicine professionals making diagnosis. Considering these findings, the importance of pre-injury neurocognitive data cannot be overstated, especially with recovery timeframe disparities between measures of self-report symptoms and neurocognitive recovery. This further demonstrates the need for concussion tools that are sensitive to the sequelae of concussive effects and can test an array of assessments domain including both symptoms and multiple cognitive functions for treating athletes with concussion. It can be argued this will increase diagnostic ability above standalone tests, especially when serial follow-up assessments are necessary.

Table 3.3: Neuropsychological domains measured in currently used test batteries.

Cognitive Processes Measured	*ImPACT*	*CRI*	*CogSport*
Attention	✓		✓
Sustained attention	✓		✓
Reaction Time	✓	✓	✓
Visual Recognition	✓	✓	✓
Information Processing Speed	✓	✓	✓
Visual Scanning	✓	✓	✓
Learning	✓		✓
Immediate Working Memory	✓	✓	✓
Delayed Working Memory	✓		
Response inhibition	✓		
Auditory - Information Processing			
Symptom Scale	✓	✓	✓

ImPACT = Immediate Post-Concussion Assessment and Cognitive Testing; CRI = Concussion Resolution Index; CogSport = CogSport: Headminder (Broglio, Ferrara, et al., 2007; Collie, Maruff, Makdissi, et al., 2003; Erlanger et al., 2003; Iverson et al., 2003)

3.2.4 Pros and Cons

Over the last 20 years, neuropsychological test batteries have become increasingly common following sport-related concussion because of their unique ability to provide information surrounding the cognitive status of the athlete. Previous decisions surrounding timing of safe return-to-play protocol were made based on the presence and severity of self-report signs and symptoms following a concussion. The problems of using self-report symptomology lie in the variability, under-rating, under-reporting, and potential for resolution before changes in cerebral functioning has completely recovered (Makdissi et al., 2001). In 2001, the CISG endorsed their use in the sporting context, resulting in sport-related concussion and management programmes receiving unprecedented attention. Consequently, neuropsychological test batteries such as CogSport, HeadMinder, and ImPACT were developed; each of which provides various measures of objective information concerning cognitive function after a concussion is sustained (King, Brughelli, Hume, & Gissane, 2014).

In total, 11 areas of neurocognition are presented from the core scales identified and listed in Table 3.1. Table 3.3 presents the cognitive processes measured and the occurrence in each of the neurocognitive test batteries. Of the 11 items on the list, only five were used across all scales: reaction time; working memory; information processing speed, visual recognition, and; visual scanning. The next most assessed areas were included in 2/3 test batteries: attention; vigilance, and; learning. Symptom scales were used in each of the three test batteries reviewed. Interestingly, none of the test batteries included the assessment of auditory processing, an impairment commonly associated with whiplash head trauma (Atcherson & Steele, 2016).

It is true the development of CNT batteries offers more than a few logistical advantages over traditional pen and pencil tests (see Table 2). However, the shift to using computerized programmes faces its challenges and limitations. Firstly, computer programmes can gather and store data, however, they are not able to interpret information, nor place clinical value of the meaningfulness of those data. Accordingly, there is an explicit agreement among researchers and clinicians involved in the evaluation of SRC that the responsibility for making diagnostic and return-to-play decisions lies with the physicians and not with the tool itself. Therein lies the problem, firstly, the requirement of trained and licensed sports medicine professionals to administer the assessments and interpret the results. This is reflected in the lack of medical staff at community and adolescent level sport (Echemendia et al., 2013). Secondly, as outlined by Echemendia et al. (2013), alternate test forms are not always equal and reaction time measures are common in computer settings. Lastly, and most importantly, is the integrity of the tool; have the fundamental psychometric properties been considered and established. Particularly in the athletic setting, CNT has not had the same level of validation as many of the traditional tests (Arrieux, Cole, & Ahrens, 2017). This also includes providing evidence of consistency for test re-test reliability and repeatability (Collie, Makdissi, Maruff, Bennell, & McCrory, 2006; Resch et al., 2013), and issues of sensitivity and specificity (Lau, Collins, & Lovell, 2011); all of which have been documented in peer-reviewed literature. The importance of CNT's providing reliability lies in the ability to accurately and dependably test, and re-test for continuous, serial and intermittent evaluation. This is ideal for the sporting context, where damage to the brain may be developing and symptoms may be worsening during the symptomatic phase of the recovery period.

Table 3.4: Advantages of Computerized Neuropsychological Assessment
▪ Ease of administration whether sole or serial assessment
▪ Decreased staffing requirements compared to medical implementation of paper-based measures
▪ Minimization of tester bias
▪ Ease of data retrieval
▪ Computer usage may capture and engage the participants interest
▪ Automated data collection, analysis of response and indefinite storage ability may allow the clinician to focus on treatment over assessment
▪ Increased security of test data and patient records if handled cautiously
▪ High sensitivity to subtle cognitive effects and the ability to demonstrate the extent of cognitive malfunction during the recovery period
▪ Test-retest reliability secondary only to standardized assessment directed by a medical professional
▪ The efficiency of the computer to measure and collect multi-dimensional objective information of performance (e.g., latency, strength, and locus of response) at levels not obtainable by human observation (milliseconds, grams, millimetres)
▪ The ability to control stimuli and stimuli characteristics
▪ Many alternate test forms
▪ Enables high level neuropsychological interpretation of the outcome and feedback within a matter of hours, regardless of location of the testee
▪ Reduced financial cost (i.e., disposable material reduction)

(Broglio, Ferrara, et al., 2007; Collie et al., 2001; Collie et al., 2003a; Johnson et al., 2011; Makdissi et al., 2001; Schatz & Browndyke, 2002; Shuttleworth-Edwards, 2011)

3.3 Components of the Neuropsychological Function Assessments

A concussion in contact sports is a complex injury from which individuals may experience a vast array of symptomology. As such, it is imperative to include a multidimensional approach when assessing for injury (Echemendia et al., 2013). This is especially true in neuropsychology of sports concussion. Typically, this assessment includes various measures of higher brain functioning that are recognised as most susceptible to the effects of a concussion (Chafetz, 2012). These higher order capacities of the brain can be listed under are the term 'cognition' (Covassin & Elbin, 2010; Lezak, 2004). The cognitive constructs reviewed below have been recognised as the most relevant following sports concussion, including; information processing speed and attention; reaction time; working memory, and; auditory processing. It should be mentioned that information processing speed refers to the rate at which a human can take in new information, reach some judgement, and formulate and execute a response. This information stimuli can be visual and auditory. It is commonly assumed a slowing of reaction time reflects a diminution of processing speed (MacFlynn, Montgomery, Fenton, & Rutherford, 1984).

3.3.1 Vigilant attention

The assessment of attention dysfunctions represents a central area of neuropsychological evaluation following mild brain injury. Investigations involving attention have primarily focused on the ability to correctly execute a response, with a lesser focus on the extent to which cognitive deficits may relate to sustained attention (vigilance) (Pontifex et al., 2012). Vigilant attention refers to the ability to maintain focus and alert to a specific stimulus or set of stimulus over a prolonged period (Warm, Parasuraman, & Matthews, 2008). Although continuous tasks appear to hold utility in cognitive assessment, there is no commonly used measure. Several attempts have been made to measure attentional deficits using typical vigilance tasks (e.g., working memory by span, and; serially tested speed by timed tasks) where the participant is asked to detect infrequent targets over a specific period (Lezak, 2004; Pontifex et al., 2012; Robertson, Manly, Andrade, Baddeley, & Yiend, 1997; Whyte, Grieb-Neff, Gantz, & Polansky, 2006). In these tasks, a loss of vigilant attention can manifest as a decline in reaction response time or a decrease in measured response accuracy.

Initial evidence by Cicerone (1997) demonstrated that the examination of vigilant attention following mild-traumatic brain injury (mTBI) might provide additional information into injury-related cognitive deficits. In the study, the 57 subjects who sustained mTBI were prone to task omission errors, with prominent deficits associated with increases in task difficulty while performing a continuous task in comparison to healthy subjects. Robertson and colleagues (1997) reported similar results when comparing 34 mTBI patients with healthy subjects using the Sustained Attention to Response Task (SART); a continuous reaction time task. It was proposed by the authors that due to the task characteristics of simplicity, predictability, and rhythmicity, waning attention could be viewed as a speeding up of the reaction task stimuli over time. However, this might be due to participants setting up a patterned response, requiring less effort resulting in the most errorful way of performing tasks. Interestingly, in healthy participants, once an error was perceived, a return of effortful sustained attention to the task was noted, whereas, mTBI patients showed a significantly reduced tendency to improve task performance. This suggests that continuous efforts provide greater insight into failure than a simple response.

More recently, Pontifex and peers (2012) illustrated the extent to which failures in vigilant attention were related to mTBI in eighty-university based recreational athletes. The authors used the IMPACT and a task to assess the inhibitory effects of cognitive control (a modified flanker task). The outcome of this study suggests a link between the ability to maintain attention may be related to mTBI. In addition, the authors suggest findings consistent with Cicerone (1997) with persons having suffered a concussion resulting in a greater number of omission errors and more frequent sequentially occurring omission errors.

Although there is a lack of investigative research involving SRC and vigilant attention, there is enough evidence surrounding mTBI and cognitive deficits relating to a loss in ability to maintain attention for prolonged periods of time. Following mTBI, there is an apparent reduction in attentional effort leading to a greater number of accidental performance errors (e.g., slowing of reaction time, omission errors and sequentially occurring omission errors) on continuous cognitive tasks. Therefore, it is reasonable to argue that vigilant attention is an important construct for detecting and measuring brain injury following SRC.

3.3.2 Reaction Time

Prolonged reaction time is one of the most sensitive indices of information processing speed, and of the subtle deficits in neuro-cognition following concussive injury (Eckner, Kutcher, Broglio, & Richardson, 2013; MacFlynn et al., 1984). Testing simple reaction time (SRT) refers to an individual simply responding to a set occurrence of a stimulus as fast as possible (Shelton & Kumar, 2010). It does not require a decision or choice to be made and is one of the most basic measures of information processing speed (Woods, Wyma, Yund, Herron, & Reed, 2015). For example, an individual may be required to hit a button on presentation of a light turning on. Further evaluation of the nature of sensory-motor speed can also be reflected in the complexity of the task. Reaction time increases disproportionately with increased task complexity (e.g., the inclusion of integrated skills such as scanning, visual recognition and perception). In healthy young adults, mean reaction time is reported to be ~210 milliseconds to detect a visual stimulus (Narayana, 2009). Still, due to momentary lapses in attention, a considerable amount of variation is expected (Mohan et al., 2010). Literature has associated a delay in reaction time with acute concussion injury, sanctioning the use of such an assessment for identification in SRC (Collie et al., 2006; Makdissi et al., 2001; Stuss et al., 1989; Warden et al., 2001).

Early impairment of SRT in sports-related concussion was documented by Maddocks et al. (1995) who studied a sample of 130 Australian Football League Athletes. Of the 130 athletes involved in the study, 10 suffered a concussion during match play. Evidently, they displayed slower responses to the reaction time tasks in comparison to prior baseline data. In the early 2000's, the use of CNT's became vastly more popular for detection and injury-based monitoring due to the sensitivity and specificity of the assessments available at the time. Erlanger (2001) demonstrated the use of a commonly used web-based concussion assessment tool (HeadMinder: CRI) and found that 42% of subjects diagnosed as concussed tested positive for a significant delay in SRT. In this study, complex reaction time was also measured and identified in 50% of the subjects included. Consistent with these findings, Warden et al. (2001) performed a CNT using baseline assessments for fourteen mildly concussed athletes during physical activity. Re-assessments were taken at 1-hour, and 4-days post-concussion. At both re-assessments, subjects displayed a delayed SRT. Interestingly, greater delays were reported after four-days (+88 milliseconds), in comparison to baseline data (Warden et al., 2001). Typically, post-concussive cognitive impairments are prone to resolving within 5-7 days of injury (Iverson et al., 2006). The problem, however, is that athletes are displaying a slowed SRT, despite being asymptomatic and are cleared for full sporting participation (Warden et al., 2001). The importance of this lies in the situation the athletes are left in, following clearance. It could be argued that an athlete with a slowed reaction time may be less capable to respond to a stimulus during a game (e.g., placing the hands up to catch the ball), resulting in a poor performance. In a worse scenario, the athlete may be predisposed as vulnerable to further injury due to the inability to react in critical situations (e.g., placing the head in the incorrect position in a tackle situation). A slowed SRT has also been displayed using previously mentioned validated neuropsychological test batteries (Iverson et al., 2005). In 2003, Alexander Collie and colleagues found that a sample of 25 symptomatic Australian Football players diagnosed with a concussion, displayed significantly worse SRT in comparison to their baseline measure using the CogSport neurocognitive test battery (Collie et al., 2003). Similarly, Iverson et al. (2005) evaluated 72 amateur athletes diagnosed with a concussion and identified a strong relationship ($r = 0.60 – 0.70$) between composites of reaction time and processing speed measures. The authors used the ImPACT test battery compared with traditional neuropsychological and previously validated measures of scanning and tracking aspects of attention and information processing speed in the form of Symbol Digit Modalities Test (Iverson et al., 2005). Although the tests conducted may differ, the underlying constructs measured are similar, therefore validating the use of SRT as a plausible identifier to assist in the identification of SRC (Collie et al., 2003; Iverson et al., 2005).

3.3.3 Working Memory

Memory involves a series of processes which are dependent on many levels of brain function such as encoding, storage and retrieval (Chafetz, 2012). There are many individual factors that can affect specific areas of memory processing. Consequently, the performance of a memory assessment can reflect common patterns of memory deficits associated with specific neurologic impairment. According to patients who have suffered a minor head injury, as seen in sport concussion, may experience the following (Chafetz, 2012):

- Variable learning across numerous trials
- Immediate recall demonstrates variability

- Delayed memory can be variable but often no worse than immediate memory (no forgetfulness)
- Demonstrates good recognition of presented information but may exhibit a greater number of errors (false positives).

This pattern of memory problems can be associated with immediate and working memory (WM). WM can be defined as the temporary storage and manipulation of information over a short period of time (Green, Keightley, Lobaugh, Dawson, & Mihailidis, 2018). In sport neuropsychological literature, WM capacity is deemed essential for cognitive abilities such as reasoning, comprehension, problem solving, skill acquisition, attentional and perceptual changes, and decision-making ability (Furley & Memmert, 2010; Mayers, Redick, Chiffriller, Simone, & Terraforte, 2011). The necessity for athletes to maintain sport-task relevant information during distracting in-game stimulus is transparent, both for optimal performance and physical safety. Studies of working memory have explored concussion using both isolated and combined cognitive screening measures, and have typically used a baseline or control-group comparison.

In 2003, Erlanger et al. examined the relationship between symptoms severity (number of immediate symptoms, number of symptoms at re-test, and duration of symptoms) and the characteristics of concussion in forty-seven athletes. All participants were seen for a follow-up assessment at 48-hours post-injury. This paper was one of the first to document empirically derived indicators of the clinical course of post-concussion symptom resolution. The authors found athletes who had memory problems at the follow up assessment 48-hours post-injury had significantly more symptoms, longer duration of symptoms and scored lower on other neurocognitive tests.

Baillargeon et al (2012) compared the effects of recent concussion (<1-12 months) on working memory in 96 asymptomatic individuals. WM performance was measured in youth (aged 9-12 years), adolescents (aged 13-16), and adults (18 or above) who had sustained a concussion compared to uninjured controls who were age-matched. This study used an oddball task; the Brown-Peterson test. Interestingly, only adolescents showed significantly lower performance scores following immediate memory. Similar results were found by Keightley et al. (2014), who investigated the changes in verbal and non-verbal WM performance in 15 youth / adolescent (ages 10-17 years) participants. The participants in this study were between 9-90 days post-concussion with 14/15 reportedly symptomatic. Both verbal and non-verbal WM accuracy were scored significantly lower when compared with a control group. One limitation in these studies is that they both appeared to have scored accuracy, but not performance error. An understanding of what performance errors lead to accuracy decline could be helpful when developing concussion assessment tools (Green et al., 2018).

Recently, Green and colleagues (2018) explored the relationship between WM memory performance (including error type and frequency) pre-and-post concussion in 21-youth (aged 10-14 years) participants. Comparisons showed inferior performance scores post-test (lower verbal WM accuracy, greater verbal and non-verbal WM false alarm errors, and greater verbal WM missed errors). The findings from this study suggest false-alarm errors might provide valuable information acutely post-concussion.

There are many neuropsychological memory tests ranging from standalone measures to comprehensive test batteries. Selection of the appropriate measure requires an understanding of the typical patterns of memory impairment. The most common memory dysfunctions resulting from SRC are related to immediate working memory (Chafetz, 2012). Collectively, these findings suggest that WM should be part of a cognitive or neuropsychological evaluation following a concussion injury.

3.3.4 Auditory Processing

Concussion is a complex process that can involve a range of individual and overlapping symptoms. Consequently, it is essential to include a wide variety of assessments when evaluating the injury. For example, the comprehensive neuropsychological test battery ImPACT assesses executive functions of attention, processing speed, working memory, and task vigilance. However, these measurements are entirely based on visual stimuli, an observation which is common to neurocognitive test batteries. Recent evidence suggests focal and localised brain damage to various structures involved in the auditory pathway can disrupt auditory processing (Białuńska & Salvatore, 2017; Turgeon et al., 2011). The exact cause or location of the auditory impairment in the brain is not known, however, an association between mTBI in the form of whiplash has been connected to auditory processing impairment (Atcherson & Steele, 2016; Van Toor, Neijenhuis, Snik, & Blokhorst, 2006); a common injury mechanism seen in motor vehicle accidents and during collisions in contact sports (especially in rugby). Auditory processing refers to what we do with sound once we hear it and is one of the more difficult and demanding tasks our brain must perform. This can involve sound detection, discrimination, tone recognition, pattern recognition, ipsilateral sound differentiation, and dichotic listening ability (Atcherson & Steele, 2016; Turgeon et al., 2011). To put plainly, auditory processing is the ability to extract meaning from sound in a fast and accurate manner; this is underpinned by integration from auditory, sensorimotor, and cognitive networks. For example, a person may be required to listen to single or multiple sound stimuli, concentrate and press the corresponding button within a specified timeframe (e.g., the auditory vigilance task (Pang et al., 2006)). Despite this understanding, there is a noticeable scarcity of investigatory research surrounding the adverse effect sports concussion has on auditory processing (Bergemalm & Lyxell, 2005; Białuńska & Salvatore, 2017; Turgeon et al., 2011), although inferences may be made from similar impairments following mild traumatic brain injury (unrelated to sport). One of the first investigations of auditory processing deficits following head injury came from Cockrell and Gregory (1992), who found speech recognition deficits in 16% of children suffering from a mild or a severe head injury. In 2005, Bergemalm & Lyxell measured brainstem responses involving various auditory tests. The authors found that 58% of subjects who previously suffered a closed head injury, performed poorly on various auditory tests. An important finding in this study saw 80% of those found with an auditory processing disorder, also failed one or more cognitive tasks, compared to 44% among those with no signs of auditory dysfunction. More recently, Turgeon et al. (2011) investigated the impact of SRC using a test battery of five auditory dysfunction tasks on 16 university soccer and football athletes, eight of whom had suffered from a SRC. Of the eight concussed athletes, five presented with an auditory processing deficit in one or more of the five tasks used in the test battery. In contrast, all the control group presented with a normal auditory process. The findings were like both studies from Cockrell et al., and Bergemalm & Lyxell among mTBI subjects. The profile of auditory processing deficits in concussed athletes appear to be heterogeneous; a finding which may be explained by the varying mechanism of injury. It could be argued that auditory processing should be central to SRC evaluation due to the high number of whiplash injuries seen in contact sports, a mechanism linked to auditory processing impairment (Koh, Cassidy, & Watkinson, 2003). Collectively, these findings provide justification for future research into auditory processing deficits following concussion, including the possible relationships with other cognitive domains (e.g., vigilant attention). This might allow for a greater understanding of brain function following SRC.

3.3.4.1 Auditory Processing Reaction Time (APRT)

To the author's knowledge, none of the concussion assessment tools mentioned in this review measures any area of auditory processing dysfunction; a reflection of the lack of understanding and under-evaluation within SRC assessment tools. A slowed auditory reaction time, however, has been widely used to evaluate neuro-cognitive responses in sports. As such, the effects of simple reaction time (SRT) in comparison to auditory reaction time (ART) have been investigated.

Early research by Pain and Hibbs (2007) investigated the effects of a simple auditory reaction time vs simple visual reaction time in athletes. The results showed that simple auditory reaction time has the fastest reaction time for any given stimulus. Shelton & Kumar (2010) added to the paradigm of research by demonstrating that an auditory stimulus only takes approximately 8-10 milliseconds to reach the brain, while visual stimuli take approximately 20-40 milliseconds. The implication of this lies in the speed of the information processing in the motor cortex. The faster the stimulus reaches the brain, the faster the reaction. These findings were consistent with Shelton and Kumar (2010) who found that auditory reaction time was faster in comparison to simple reaction time using the DirectRT computerised programme; a software used for generating psychological experiments (Stahl, 2006).

Considering the injurious role sport plays in concussion rates, verifying its impact on neurocognitive status is of utmost importance as both speed of movement and quick reactions are prized qualities in athletes. Therefore, it is reasonable to suggest that an impaired auditory reaction time could play a significant role in sporting performance (e.g., communication during play calling). The faster the information is processed, the faster the necessary response is transmitted for the required motor reaction. A slowing of motor reaction from auditory processing could have health and safety implications in sport also (e.g., not preparing for a tackle situation resulting in injury) and, therefore, demands significant attention in the identification and monitoring of concussion.

As we continue to understand the pathophysiological effects of SRC on cognitive functions, there is a responsibility to manage the injury better. Although investigations of auditory processing in the realm of SRC are scarce, there is enough information to determine that auditory dysfunction and sports concussion are inter-related. Therefore, testing of integrated auditory processing such as auditory reaction time should be added in assessment batteries following minor head injury in sport.

3.3.5 Fatigue and Cognition

Mental fatigue is recognised as a non-specific psycho-physiological occurrence (Gupta, Kar, Gupta, & Routray, 2010). It is a state characterised by cortical deactivation resulting in a decline in alertness, mental performance, and a reduced cognitive efficiency. Fatigue can be manifested in any oculomotor activity associated with any visual information intake. It is also accompanied by a reduction in cognitive function and psychomotor function; the ability to coordinate timely and appropriate responses to an external stimulus (Gupta, Kar, Gupta, & Routray, 2010). Time-of-day dependent changes in human cognition are also modulated by the internal system called the circadian clock (Wright Jr, Lowry, & LeBourgeois, 2012). This system interacts with sleep-wakefulness processes, which regulate brain arousal, neurocognitive and affective processes. Experiments involving tests of cognitive constructs such as vigilant attention and auditory processing, (Collins & Capps, 1965; Gupta et al., 2010; Pang et al., 2006) and reaction time (Gupta et al., 2010; Shinde & Pazare, 2013), as well as the time of day dependent changes in cognition, have all been used as a way of determining the effect fatigue plays on mental status.

In 2005, Pang examined mental fatigue based on the theory of cortical deactivation occurring during fatigue using an auditory vigilance task (AVT); a measure of auditory reaction time. In this study, five-individuals were recruited to understand the role sleep restriction plays on the sensitivity and reliability of the AVT. Each participant performed the AVT serially (once per hour for twenty-five hours). The results indicated the lowest performance scored was between 3-7am. This finding is consistent was previous research explaining how our biological clock modulates our hour-to-hour waking behaviour, as reflected in fatigue, alertness and performance (Van Dongen & Dinges, 2000). Also, earlier studies of circadian rhythm and core body temperature have suggested body temperature peaks relating to performance change. In 2003, Hull, Wright Jr and Czeisler found changes in body temperature are associated with changes in cognitive performance of alertness using the Digit Symbol Substitution Task (working memory) and the Psychomotor Vigilance Test (reaction time). In this study, performance peaked around 6-10pm and was worst around 6 am. Pang's study displayed similar findings with performance accuracy prone to lapses around 4 am. In addition to cognitive productivity exhibiting a decrease during night-time and very early morning, a temporary drop in alertness and performance during the afternoon has been evidenced in laboratory studies using various cognitive tasks since the mid-1900's (Blake, 1967; Monk, 2005). This mid-afternoon dip is partially explained by meal ingestion (Slama, Deliens, Schmitz, Peigneux, & Leproult, 2015); however, it is also reflective of the 12-hour harmonic of the circadian clock (Van Dongen & Dinges, 2000; Wright Jr et al., 2012).

In a study of fatigue in human drivers, Gupta et al (2010) presented objective methods for assessing mental fatigue using an auditory vigilance test and a visual response test. The outcome of this study is consistent with the studies from Pang et al (2005) and Hull et al (2003) which is suggestive of auditory vigilance tests and visual reaction task being the preferred attention-based tasks when detecting fatigue; a finding consistent throughout the literature (Collins & Capps, 1965; Shinde & Pazare, 2013).

3.3.5.1 The Influence of physical exercise on fatigue: duration and intensity

Anecdotal descriptions of changes in the ability to perform mental tasks during and after exercise are common. For some, these changes include increased awareness and clarity of thought. For others, exercise leads to reports of mental disorientation and difficulty in attention and decision making. Consequently, the relationship between acute bouts of exercise and neurocognitive performance tasks has gained a lot of attention in the realm of exercise and cognition. According to Lambourne and Tomporowski (2010), the role of exercise on cognition has been extensively researched with over 150 empirically derived studies completed in the last half-century. Much of the early research on the relationship between physical activity and cognition have utilised arousal theories. Common amongst these theories is the notion that performance of cognitive functions is dependent on the physical task demands. One method typically used for examining the exercise-related effects on cognition is to test predictions generated from ideas such as the inverted-U theory (Figure. 3.2) first described by Yerkes and Dodson in the early 1900's (Lambourne & Tomporowski, 2010).

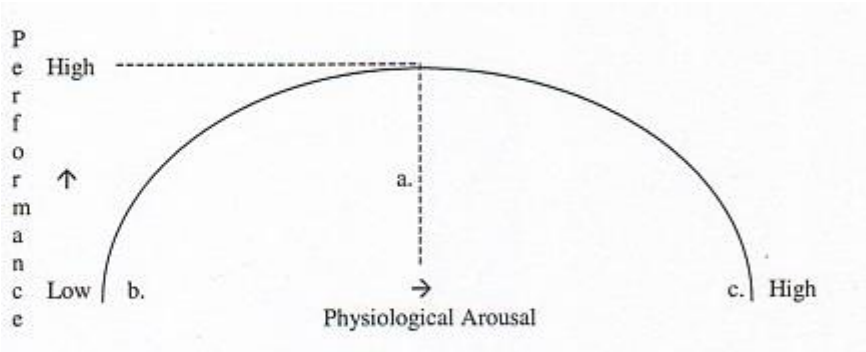

Figure 3.2.: The Inverted-U relationship: an early explanation of the relationship between arousal and performance. *Adapted from* McNally (2002).

Several isolated studies and meta-analysis have demonstrated this relationship (Lambourne & Tomporowski, 2010; McMorris & Graydon, 2000; McMorris, Sproule, Turner, & Hale, 2011). McMorris and Graydon (2000) explain how cognitive performance improves with systemic alterations in physiological markers up to a certain point (moderate intensity exercise (<70%HRmax)), then deteriorates as arousal increases towards its maximum. Only in recent decades, however, has the relationship between acute exercise and cognition formed some clarity due to contradictory findings. This ambivalence is due to, in part, the different exercise protocol, methods of exercise assessment, and the mode of exercise employed in the vast number of peer-reviewed publications. For example, according to Hancock & McNaughton, (1986), acute periods of physical activity improve information processing ability in adults. On the other hand, Côté, Salmela, & Papathanasopoulu (1992) found no such benefits, while Cian, Barraud, Melin, & Raphel, (2001) even found deteriorative effects. These contradictory findings have led to the identification of factors which may affect the experimental outcome: 1) the physical fitness of the subjects; 2) the intensity and duration of exercise, and; 3) the nature of the cognitive task administered (Arcelin, Brisswalter, & Delignieres, 1997).

As stated above, the duration of acute exercise is claimed to affect the performance of tasks measuring cognitive processes. This idea was exemplified by Clarkson-Smith & Hartley (1989) and Hogervorst, Riedel, Jeukendrup, and Jolles (1996), who found that sensorimotor cognitive performance (recognition, reaction time, working memory) improved immediately after sub-maximal exercise (<130 heartbeats per minute, 20-40 minutes) in older adults and endurance athletes, respectively. This effect was also demonstrated more recently by Chang and colleagues in 2015 who showed that twenty-minutes of moderate intensity exercise (65% heart-rate reserve) resulted in greater cognitive scores when compared to 10-and-45-minutes. Crush and Loprinzi (2017) similarly added to the paradigm by demonstrating how the cognitive task complexity may be influence following 60-minutes of moderate intensity cycling having rest periods at 1, 15, or 30-minutes. The authors noted no differences between rest-durations; however, important observations were made including 1) short recovery time (i.e. 5-minutes) may be less favourable when addressing planning-based cognitive functioning but advantageous for memory function. This recovery-specific effect on cognition may be based on exercise duration, yet more research is needed to confirm these findings.

In contrast to this group of pragmatic studies, Cian et al (2001) proposed that prolonged exercise at submaximal intensities led to a reduced cognitive performance. In this study, a continuous two-hour treadmill protocol was performed at 65% of maximal oxygen uptake, which resulted in significant alterations to memory, visual discrimination, and psychomotor abilities; however, one could argue that exercise-related heat stress may have influenced the results with dehydration being a known independent moderator of cognitive performance (Hancock and McNaughton, 1986). What these studies demonstrate is that acute bouts of moderate intensity exercise appear to confirm the inverted-U theory by eliciting general improvements in cognitive processes. This improvement is, however, dependent on the duration of the exercise task; longer durations (>60-minutes) may result in impairment of cognitive performance, despite similar intensities.

In 2007, Covassin and colleagues used the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) neuropsychological test battery to assess the effects of a maximal exercise test on cognitive function in 102 male and female recreational athletes. Participants in the test group (n=54) were asked to perform a maximal treadmill exercise test to maximal oxygen uptake or volitional exertion. The results suggest that a maximal exercise test attenuates a limiting effect on cognition when tested fifteen-minutes following activity (Covassin, Weiss, Powell and Womack, 2007).

Hüttermann and Memmert (2014) displayed findings suggesting the intensity of high-intensity exercise could impair cognitive functioning. In this study, eleven-university students (non-athletes) and 8-athletes were recruited to examine the relationship between the intensity of an acute bout of physical exercise and visual attentional performance. The intensities of the exercise was 50, 60, and 70% of age-predicted maximal heart rate when doing ergometric cycling. As predicted by the authors, the non-athlete group displayed a relationship consistent with the inverted-U shape; cognitive performance increases until a particular point of exercise capacity (60%) after which it starts to decrease. Interesting, a linear relationship was shown for the athlete group, suggesting that physical fitness is an independent moderator in the exercise-intensity-cognitive relationship. One could argue that using age related-heart rate may have presented a limitation surrounding accuracy (e.g., regular exercise is associated with lower resting heart rates). Additionally, the high-intensity condition was set at 70% of age-related heart rate. As such, the linear relationship reported for athletes suggests that the perception of effort is moderate at best and not intense enough to elicit potential deteriorating effects. Lastly, the exercise mode (ergonometric cycling) could affect the performance effect. Lambourne and Tomporowski (2010) demonstrated that cycling when compared to running, would engage less high-order attention and affect performance negatively at the same intensities. The increased attentional demands of running have been attributed to the cognitive awareness needed to hold and maintain postural sway in a standing position and during gait (Fraizer & Mitra, 2008). Similar results were demonstrated recently by Rattray and Smee (2016) who showed that simple working memory is positively affected by constant moderate exercise and adversely affected (non-significantly) during cycling exercise conditions in which power output might vary to include intermittent low and intermittent high-intensity efforts. Smith et al (2016) also examined the effect of short duration, moderate and high-intensity treadmill running on reaction time using the Go/no-go task; a task previously developed by Pontifex, Hillman, & Polich (2009). In this study, 15 habitually trained individuals (9-males) were recruited. The results demonstrated that high-intensity running caused a significant decrease in simple reaction time and a higher number of omission and decision-making errors. These findings align with work by Duncan, Smith, & Lyons(2013) who investigated the relationship between cognition and running speed with largest decrements in cognition taking place at 90% heart rate reserve.

Using the model of (Dietrich & Audiffren, 2011) for psychological consequence to exercise, the minimal decrements displayed from Rattray's study might not only be due to the exercise mode and intensity, but also the low computational requirements of the memory task. This finding provides essential information about sports concussion injury.

With the effects of concussion developing and changing subtly during the symptomatic phase, assessments of long durations may not reflect the moment by moment physiological changes likely to influence the brains cognitive functions (Rattray & Smee, 2016).

A vast amount of scientific evidence supports the notion that physical exercise influences change in cognitive functioning. However, several independent moderators in these studies are related to the overall effect on cognitive performance. Firstly, it appears larger negative effects on cognition were observed during aerobic activities involving running protocols, rather than ergonometric cycling protocols. While both utilise large muscle groups, difference in muscle recruitment patterns would result in different energetic contributions to exercise. Cycling requires a much lower energetic cost compared to running, as well as less attentional focus to account for postural sway during gait locomotion. Despite this review drawing on results from studies of aerobic exercise, it is reasonable to propose these findings do confirm that exercise mode can influence cognitive outcome.

Secondly, factors responsible for diverging results appear to be related to variations of exercise intensity, duration, hydration status, and time of day. As such, athletes are often in an exerted state when being assessed on the field of play. Separating exertional effects from physical and cognitive performance decrements presents a challenge for the athletic trainers and team physicians. Therefore, it is reasonable to suggest that for accurate identification of cognitive effects following a concussion, neurocognitive tests must be able to recognise and differentiate between deficits related to head injury and acute fatigue. Moreover, it appears when using a neurocognitive test battery for a head injury, the examination should not be delivered immediately after a practice or a game session. It appears the determination of the role fatigue plays has important implications in sports-concussion.

3.4 Modern Technology: Electronic Devices and Applications

The introduction of mobile technologies in the form of smartphones and tablet devices has opened the door to innovative health delivery systems. In 2012, an estimated 1 billion people used smartphones devices (Lee et al., 2014). A change of pace accelerating this growth with current estimations projecting this figure to be above 2.5 billion, at present (Clarke, 2017). This demonstrates the importance that smart-devices play in our everyday lives. This growth has led to numerous efforts toward producing mass-market remote software applications (Apps) for the assessment of concussion. The first concussion-related App was established in the marketplace mid-2009 (Lee et al., 2014). The number of Apps available, as expected, has since increased. Several independent Apps have emerged more recently such as the SWAY Balance Mobile Application (Amick, Chaparro, Patterson, & Jorgensen, 2015), and HeadCheck (Davis et al., 2015), adding to the large corpus of concussion-related information currently available. Translating important information not only to health and sports medicine professionals, but also to management staff, coaches, parents of young athletes, and athletes are the foundation of which these apps are laid. Empowering individuals with concussion-related information is a step forward in improving the early recognition of possible concussion, especially at the amateur and youth level sport, where medically trained persons are not commonly present. Such applications could be used not only to measure immediate symptomology, as seen in current pitch-side assessment protocols, yet, could also provide and store vital information pre- and post-concussion (continuously or intermittently). This would enable the monitoring of individual progress with standardised assessments, or potential regression as a result of cumulative head injury over a (multiple) seasons (Stuart, Hickey, Morris, O'Donovan, & Godfrey, 2017).

However, the ease of use and availability of concussion-related Apps is also followed by an apprehension of who is using them, and how they are used (e.g., interpretation of result) (Lee et al., 2014). It is, therefore, necessary that the applications are true representations of current best-practice information. The content and quality of some apps have been questioned, as the knowledge and experience of the persons involved in app development may not be suitable without additional help from informed health professionals. Additional concern follows the feasibility and acceptance of widespread use by professionals in the sporting industries is done so with hesitance (Lee et al., 2014). This concern is also directed at development issues of data security (Bauer et al., 2012; Marshall & Haley, 2000), the impact of motivational influences on test performance (Coffin & MacIntyre, 1999), the learning effects and familiarity of CNT (Del Rossi, Malaguti, & Del Rossi, 2014; Oliveira, Trezza, Busse, & Filho, 2014), generational differences (Schatz & Browndyke, 2002), and human-computer factors that influence the App development and design of tasks.

Instruments such as the SCAT (5th Edition) and ImPACT, are still the backbone of concussion-related assessment worldwide. Although not essential, smartphone and tablet device Apps have the power to present information while facilitating documentation, providing new scope into the management of concussion in sport. The rise of smartphone and mobile technologies has created the opportunity for the development of other assessment instruments provided they are targeted at the appropriate user populations and comply with the referenced criteria of a concussion assessment tool as recognised by the CISG (McCrory et al., 2017).

3.5 Summary

The neurophysiological and biomechanical effects following sport-related concussion is well documented (Giza & DiFiori, 2011; King et al., 2003). Evidence suggests stand-alone measures are not sufficient in the detection of such a developing, and changing injury where physical signs and symptoms cannot be predicted. To this end, the CISG called for a multi-faceted approach in the detection and monitoring of concussion injury in sport (McCrory et al., 2017; McCrory et al., 2009; McCrory et al., 2013). Several current CNT’s are available which integrate signs and symptoms checklists and neurocognitive test batteries including areas of cognition that are frequently damaged following injury (Collie, Maruff, Makdissi, et al., 2003; Iverson et al., 2003). Although such tools provide valuable information regarding changes in specific areas of cerebral functioning, an ongoing concern has been recognised which surrounds the use of current CNT’s for gathering sensitive, reliable, and repeatable data.

Chapter 4. Design and implementation of the Concussion Assessment Tool

In developing the Concussion Assessment Web-App (CAWA), we attempted to address a variety of issues associated with concussion assessment protocols. The sections below outline the test inclusion criteria and other problems that needed to be solved.

4.1 Test Inclusion

Following a review of the existing literature, it was determined that neuropsychological assessment forms are an essential part of the screening, diagnosis and general assessment of sport-related concussion (McCrory et al., 2017). The inclusion of the four-neuropsychological measures was chosen through identification of cognitive domains susceptible to injury following sports-related concussion. Moreover, many relevant studies and concussion test protocols have not included the assessment of auditory dysfunction. However, it has been suggested auditory processing is susceptible to impairment following concussion (see section 3.3.4) and with the potential advantage for bilateral evaluation (left and right ear), an implementation of an auditory reaction time was included in the test battery.

The list of tests/tasks is as follows:

1. Concussion red-flags (CRF)
2. Concussion Symptom Inventory (CSI)
3. Simple (visual) reaction time (SRT)
4. Complex (visual) reaction time (CRT)
5. Digit-Span-Backwards (DSB)
6. Auditory reaction time (ART)

The first test is the 'Concussion Red-flags', consisting of questions to determine whether the injury is severe and requires immediate assistance. If injury does not need immediate medical care, the user proceeds to the Concussion Symptom Inventory (CSI); a 12-item symptom checklist where the user answers subjectively. To account for learning effects, and to improve user attention, the order of the four-cognitive measurement task (3-6 above) are assigned randomly each time the tool is administered.

4.2 Problem Solving

The rationale for undertaking this project is set out under the following key issues for the concussion assessment tool development.

1. Device details
2. Duration – Administration Time
3. Timing Accuracy
4. Web-App Layout

Device Details

A Web-app implementation was chosen as it runs in a web-browser and will work on any device; computers, laptops, mobile smartphones, tablets, and under various operating systems that support a modern web-browser. The main target device is a smart phone due to its widespread use and utility in varying contexts. In addition, smartphone devices have proven competent in the application of previous neuropsychological tools.

As per item 2 of the development list (see chapter 2), it was vital that there was just one implementation of the tool to maintain and that it worked across any modern device. Additionally, as per item 3 on this list, it would work locally (without a network connection until one was available). After a review of the many Web-app software development frameworks available, Meteor (an open-source JavaScript web framework written using Node.js. - https://en.wikipedia.org/wiki/Meteor_(web_framework)) was chosen, primarily because of its support for offline operation.

Duration - Administration Time

One of the chief design goals of the development was to keep the administration time as succinct as possible. It is understood that concussion causes lapses in concentration and can be medically unsafe to concentrate for long periods to time. Other neuropsychological concussion tools ImPACT, CRI, and CogSport are reportedly <20-minutes running time to complete. With this in mind, it was vital to use brief tests such as the CSI as a precise and empirically derived symptoms scale.

Timing Accuracy

Neuropsychological tests heavily rely on consistent, and accurate (millisecond precision) presentation and response timing for all persons. Even the simplest stimulus-response examples still require complete synchronization between the computer's core processor and the display. Personal computers have demonstrated limitations for accurate processing time (Cernich, Brennana, Barker, & Bleiberg, 2007). More recently, the growing trend for neuropsychological tests being modified and / or developed for touchscreen smartphone / tablet technology (Amick, Chaparro, Patterson, & Jorgensen, 2015; Curaudeau et al., 2011). A study from (Wei, Morgan, & Boyd, 2014) evaluated the accuracy and sensitivity of touch screen devices on response capture and timing compared to keyboard devices using a computerised neurocognitive test battery. Wei et al (2014) found significantly improved reaction times from subjects using the tablet suggesting it is a more sensitive testing platform. To this end, the operating system and the device details are automatically recorded during operation to enable for device latency variations as part of the preceding data analysis.

Web-App Layout

The design of the Web-App layout is an essential component of the CAWA development. The appropriate design of the page-layout and user-interface included presenting and organising the information for enhanced usability and interactivity. This comprises of essential elements, such as:

- An effective page-layout
- A user-friendly interface
- The consistency of the interface

In the construction of the design, the page-layout was important in deciding what content to place on each page, and where it should go. The Web-App logo was placed centrally on the home-page (Figure 4.1) and in the right-upper corner of the following pages. This was done to ensure it was easily identifiable and communicated what the Web-App was about. The home page also included a bold headline "Concussion Assessment Web-App" and comprehensive login details to direct the user to sign up/ log in. The bold headline was continued on each page, illustrating and leading the user to the task information.

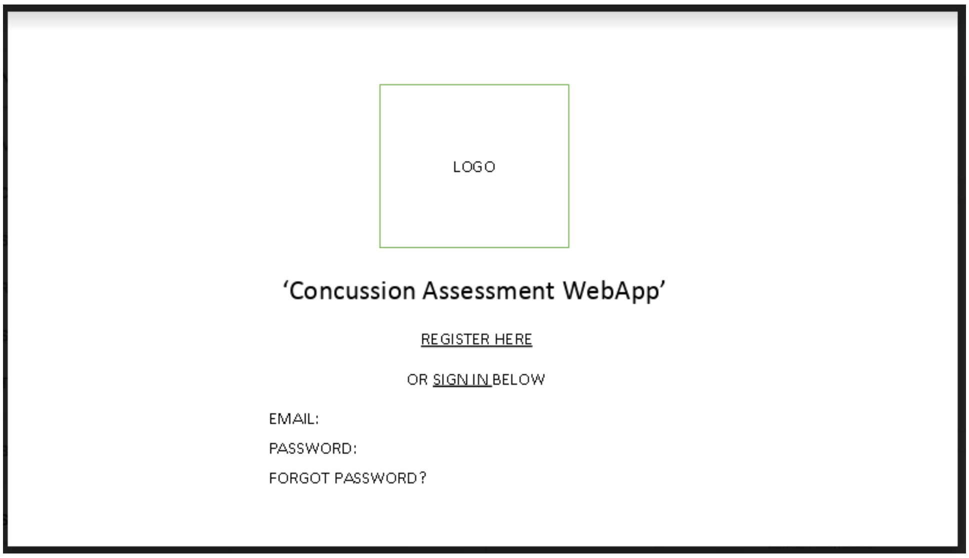

Figure 4.1: Concussion Assessment Web-App Tool: Registration / Login Page

The user-friendly element suggests it should be presented for easy-to-use navigation and relevance to users. Thus, it was essential to design an interface that allowed users to acquire the information quickly and simply in accordance with the targeted population and the type of symptoms associated with concussion injury (e.g., loss of attentional resource and concentration). Palmer (2002) suggests more navigable web interaction is also associated with greater perceived success by users. Thus, as depicted in the Figures below (4.2, 4.3), the page-layout is presented in a simplistic manner with minimal interactive elements and clear instructions directing the user to the following page.

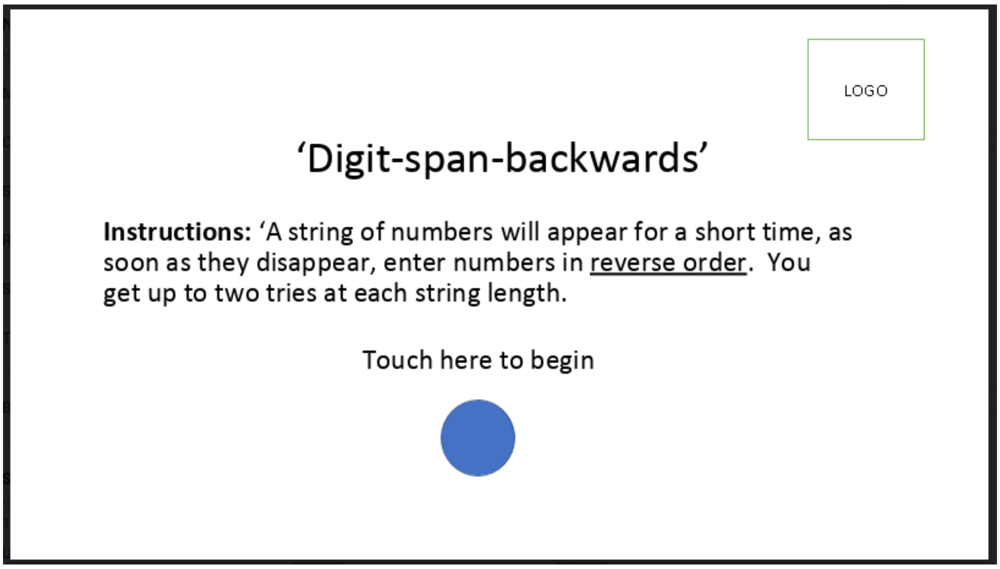

Figure 4.2: Concussion Assessment Web-App Tool: Digit-span Backwards Task instructions

Usability includes consistency of the interface and the ease of getting the Web-App to do what the user intends it to do (i.e., ease of reading, clarity of interaction, the arrangement of information, and the structure of the layout). Consistency also suggests the need for common placement of navigational tools such as buttons which will guide the user the assessment battery. As such, the interactive aspect remains central to the page layout throughout (Figure's 4.3, 4.3).

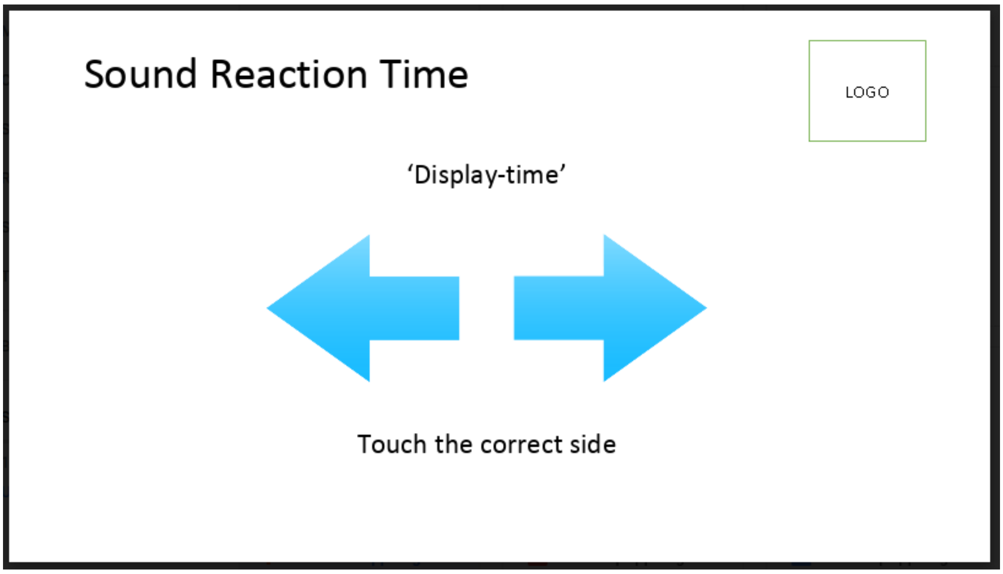

Figure 4.3: Concussion Assessment Web-App Tool: Sound Reaction Time Task

4.3 Logo and Name

The logo was designed with intention to establish and clearly communicate the message of the concussion assessment tool for measuring health, and more specifically, cognitive well-being. As illustrated by the image below (Figure 4.1), the image of a head serves as the principle area of assessment. The significance of the monitor displaying a typical heart-waveform is to demonstrate the health of the brain via access to technology, figuratively.

Figure 4.4: Concussion Assessment Tool (Web-App) Logo

The name of the Web-App was chosen by process of elimination over the course of the development process. Several possible options which were considered include: 'No KO; Head Watchdog; Head Monitor, and; Head Detective. However, the decision to name the web-App acronym 'CAWA' was based on preceding concussion tools using the same idea (i.e., ImPACT and CRI). This lead to the Concussion Assessment Web-App; an informing title using descriptive keywords, and the trending idea of acronym classification for current concussion tools applications. The logo was implemented as a scalable vector graphic (SVG), so that it would always render at its best, no matter the screen size and resolution.

Chapter 5. Investigations for reliability and sensitivity to exercise of the Concussion Assessment Tool (CAWA)

5.1 Methods and Materials

5.1.1 Participants

Twelve healthy male volunteers (mean age 22 ± 2.5 years) gave informed consent. Volunteers were recruited from programmes of Massey University, Wellington, New Zealand. Participants were screened for precluding health conditions and were excluded from the study if presented with or suffered from the following criteria: 1) a concussion within the past six months; 2) chronic migraines, and; 3) tinnitus. The research was approved by the Massey University Human Ethics Committee (Southern A, Application 16/32). A short registration form gathering demographic and sport history information and a brief two-page, 21-item questionnaire (see Appendix C) designed to collect descriptive information from each participant to determine suitability for participation in the study. It included information related to previous history of concussion (>six-months), any cardiovascular health risks, current injuries preventing involvement in running, involvement in regular physical activity, or the suffering of chronic migraines / tinnitus.

5.1.2 Protocol

The Concussion Assessment Web App (CAWA) was administered on 15 occasions over a five-day period. Participants carried out a familiarisation session before completing the App for the baseline values. The familiarisation was chosen to minimise the learning effects to obtain true baseline data. To test for App reliability following fatiguing exercise, the participants conducted a graded exercise test.

All responses were recorded on a web server and then exported into Microsoft Excel, and subsequently, IBM SPSS Statistics 25, for further analysis.

i. Exercise Protocol

Upon arrival at the testing lab at Massey University, participants listened to a description of the testing procedures and then read and signed an informed consent (see Appendix B). Following a baseline test, participants were administered a short maximal graded exercise test (GXT) on a motorised treadmill. They wore a polar heart rate monitor for assessing resting heart-rate and to monitor heart-rate throughout the protocol. Blood pressure was obtained as a health and safety screening measure using a standard stethoscope and blood pressure cuff (HONSUN Alpk2 Sphygmomanometer Standard Model HS-2000, Accoson, China) prior to warm-up. The protocol consisted of a 5-min warm up at a speed determined by the individual, which met an intensity equivalent of 11 as identified by Borg's Rate of Perceived Exertion (RPE) Scale (Borg, 1998). A short rest of 2-min was taken before protocol commencement. The warm-up speed served as the starting speed for the GXT, which is continuous and increased by one-km^{-1} every two-minutes until volitional cessation. Upon completion of the GXT, the participants passively rested for four-minutes in a seated position, then proceeded to administer the CAWA.

ii. Test-retest Reliability and Sensitivity

Following familiarisation, baseline, and post-exercise tests, participants completed follow-up tests, which occurred intermittently at 08:00, 14:00, and 20:00 hours (± one-hour) on days one, two, three, four, and five. The repeated tests (three-daily intervals) were chosen to account for reliability (i.e., no learning effect) and to gauge the sensitivity of the individual tests. Figure's 5.1 and 5.2 below graphically illustrate the repeat testing timeline and CAWA application design.

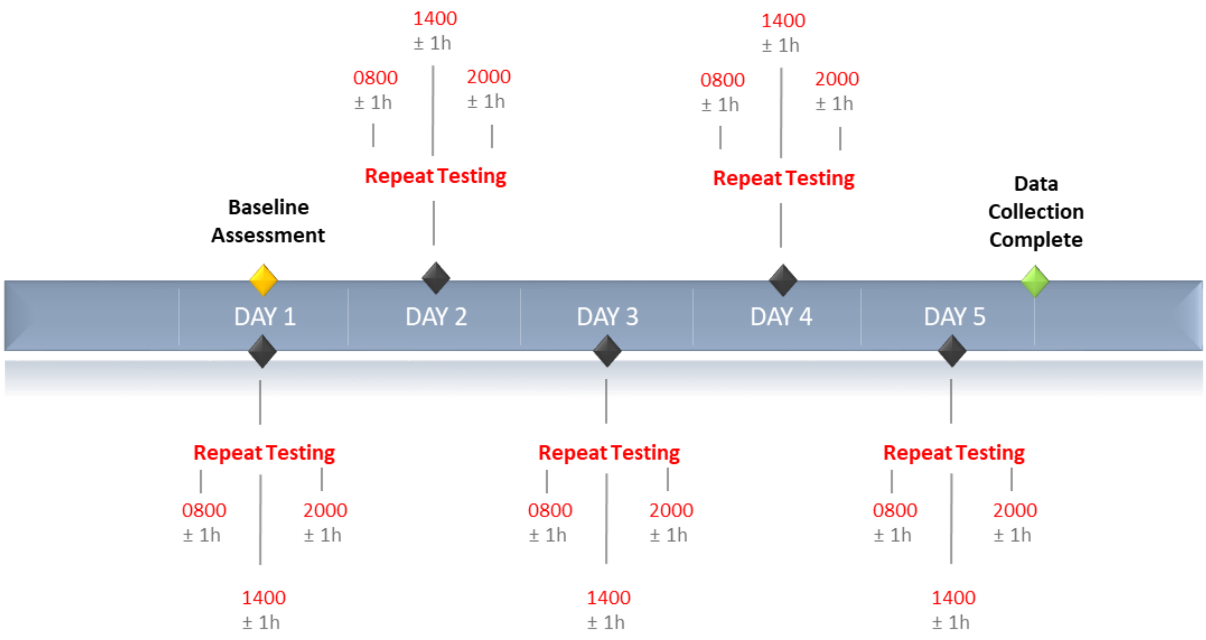

Figure 5.1. Timeline for reliability data collection. Within the five-day data collection period, participants completed the CAWA approximately 15-times through. Application procedures are described in section 5.1.3.

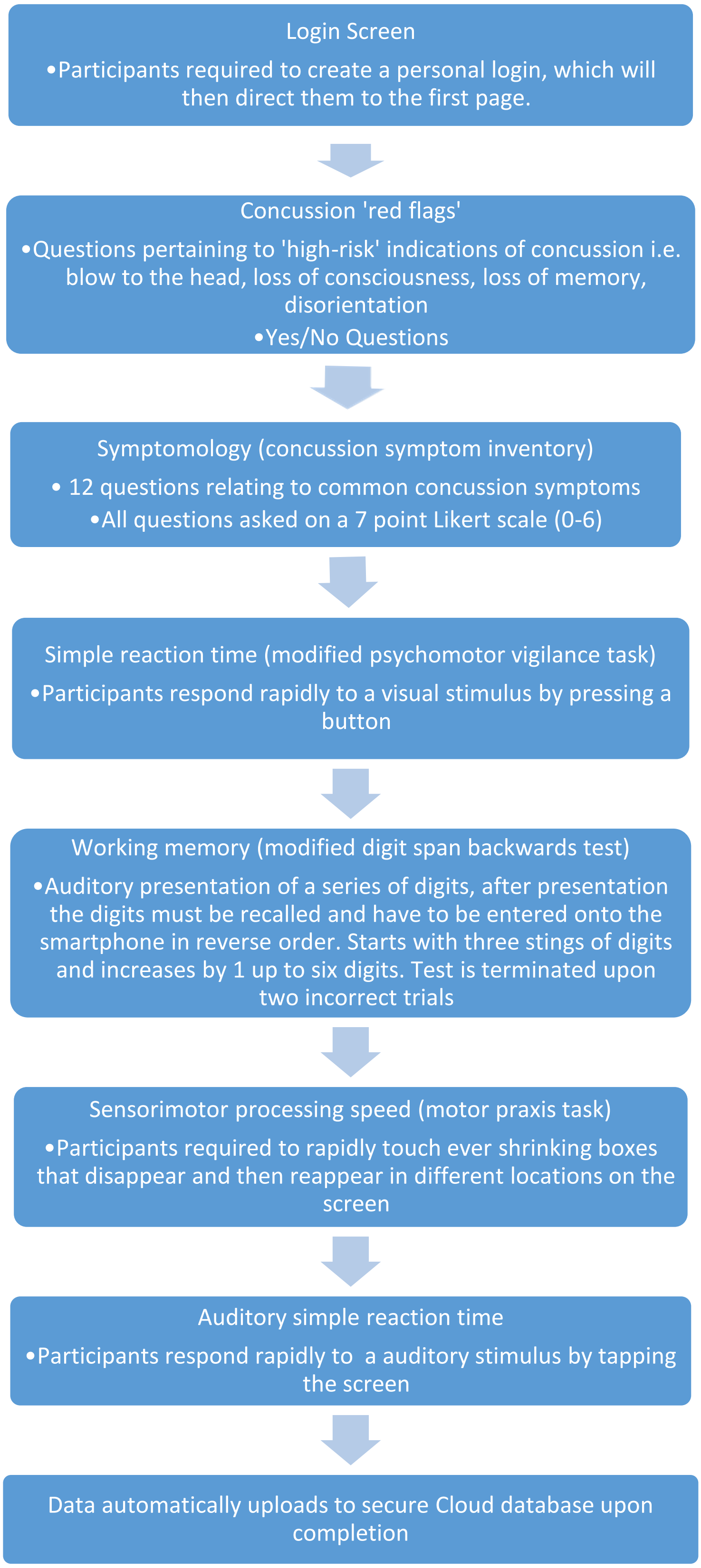

Figure 5.2. Illustration of application design. Within the five-day data collection period, participants completed the CAWA approximately 15-times through. Application procedures are described in section 5.1.3.

5.1.3 Measures

All measures were collected by exercise practitioners trained in the administration of this test battery. The stimuli are presented on a standardised tablet for the sensitivity-fatigue test and personal smart phones for the repeatability. The CAWA uses six tests as a part of a test battery including concussion red flag questions, a subjective self-report symptom questionnaire, and series of four cognitive sub-tests: Simple Reaction Time, Complex Reaction Time, Digit Span Backwards, and Auditory Reaction Time. Total time to complete neurocognitive testing for each participant was <7-minutes.

i. Concussion 'red flags'

The ‘red flags’ pertains to seven-questions (yes / no) asking about 'high-risk' indications of concussion. This is in accordance with the Sport Concussion Assessment Tool endorsed by the Concussion in Sport Group (CISG) (Echemendia et al., 2017; P. McCrory et al., 2017). The questions ask the following: 1) blow to the head; 2) loss of consciousness; 3) removal from field of play; 4/5) memory of the events that took place before / after the impact happened; 6) disorientation, and; 7) suspicion of having a concussion.

ii. Symptom Inventory

The 12-item Concussion Symptom Inventory is a summative seven-point Likert scale which was comprised of concussion related symptoms. This scale was designed to represent a concise symptom scale, which has demonstrated specificity and sensitivity for detecting concussion related symptoms (Randolph et al., 2009). Instructions to the participant read: “Answer honestly the following questions on a seven-point scale”. After reading each symptom the respondent was to touch the corresponding number that best described the current item status. Response options were designed to reflect item severity: (0) No symptoms, (1-3) moderate, (4-6) severe symptoms. Symptom items were presented in a random order and include: 1) do you feel slowed down; 2) do you feel drowsy; 3) do you feel dizzy; 4) do you have blurred vision; 5) are you have difficulty concentrating; 6) are you having difficulty remembering things; 7) do you feel nauseous; 8) do you have sensitivity to noise; 9) do you have a headache; 10) do you feel unnecessarily fatigued; 11) do you feel like ‘in a fog’, and; 12) do you have sensitivity to light.

iii. Psychomotor-Vigilance-Test (simple visual reaction time) task

Participants quickly responded to the appearance of a box in the centre of the screen by touching the box on the screen and avoided responding prematurely and inaccurately.

iv. Motor-Praxis-Test (complex visual reaction time) task

Participants quickly responded to the appearance of a random object that appeared at a random location on the screen at random intervals by touching the object on the screen and to avoid responding prematurely and inaccurately.

v. Digit-Span-Backwards (working memory) task

Participants recalled a string of numbers in reverse order. The test started with three random digits, then increased by one-digit until seven-digits are recalled or after two presentations at a digit length results in a fail to recall correctly. The test was well validated, and currently utilised as part of the SCAT (Echemendia et al., 2017). The test allocates one-second per digit. The athlete then typed this in reverse order into the keypad. If correct they then moved on to the next string length. If incorrect, a second trial of the same length, but with different numbers was repeated. If incorrect on two trials the test stopped.

vi. Auditory-Vigilance-Task (simple auditory reaction time) task

Participants quickly responded to the presentation of a sound in either the left or right ear by touching the matching left or right arrows on the screen.

5.1.4 Statistical Analysis

All statistical analysis was carried out using IBM SPSS Statistics 25. Data was checked for normal distribution using skewness and kurtosis prior to utilising any parametric analyses. A paired T-test was used to compare baseline and fatigue measures, while repeated measures ANOVA was used to check for a diurnal effect in all the tests. Cohen's effect size (Lakens, 2013) was calculated to measure the magnitude of the findings, whereby 0.2, 0.5, and 0.8 were noted as small, moderate and large effects respectively. The significance level was set at 5% ($p<0.05$), group mean and standard errors are displayed in the results.

Chapter 6. Results

Data from 11 of the 12 recruited healthy participants were included in the analyses. One-participant dropped out of the study following baseline assessment and was not included in the analysis. On average, the data included 16 (± 2.4) individual assessments using the CAWA. All 11 (mean age = 22 ± 2.5 years) participants reported no history of previous concussion or sustained a concussion during the testing process.

The Paired Samples t-test revealed a statistically significant difference between baseline and fatigued conditions for the Auditory Reaction Time test ($p < 0.000$; **Fig. 6.1**), the Simple Reaction Time test ($p < 0.009$; **Fig. 6.5**), and the Digit-span Backwards test ($p < 0.038$; **Fig. 6.9**). No other conditions displayed significant fatigue differences to baseline.

Table 6.1: Cohen's effect size for baseline vs. fatigued conditions; $m.s^{-1}$ = milliseconds^{-1}

Test	Condition	Mean ($m.s^{-1}$)	St Dev. ($m.s^{-1}$)	Effect size
Auditory Reaction Time	*Baseline*	745.3	392.7	0.13
	Fatigued	578.6	228.5	
Simple Reaction Time	*Baseline*	375.3	192.3	0.09
	Fatigued	308.1	173.7	
Complex Reaction Time	*Baseline*	687.2	317.0	0.03
	Fatigued	651.3	223.6	
Digit-span Backwards: Level reached	*Baseline*	4.364	1.027	-0.11
	Fatigued	4.727	0.647	
Digit-span Backwards: Attempts	*Baseline*	4.636	1.286	0.09
	Fatigued	5.091	1.136	

The repeated measures ANOVA identified there was a relatively small and insignificant diurnal effect across all four-neurocognitive tests for reaction times (**Fig. 6.3; 6.6; 6.8**), the number of test performance errors in the Auditory Reaction Time test (**Fig. 6. 4**), and the level and the number of attempts reached in the Digit-span Backwards (**Fig. 6.11**; **6.12**).

A summary of the participant's performance on CAWA measures (presented in raw scores) and the overall effect size for each measure was calculated using Cohen's effect size (ES) measure and displayed in **Table 6.1**.

Table 6.2: Cohen's effect size for reaction time: morning, afternoon, and night; *ES* = effect size.

Test	morning/afternoon (ES)	morning/evening (ES)	afternoon/evening (ES)
Simple Reaction Time	0.012	-0.038	-0.050
Complex Reaction Time	-0.004	-0.039	-0.037
Auditory Reaction Time	-0.015	-0.015	-0.001

6.1 Auditory Reaction Time

Total mean auditory reaction times and the mean number of test performance errors are illustrated in the figures below. Mean reaction time was significantly lower under fatigued conditions (p <0.000). No other values were deemed significantly different.

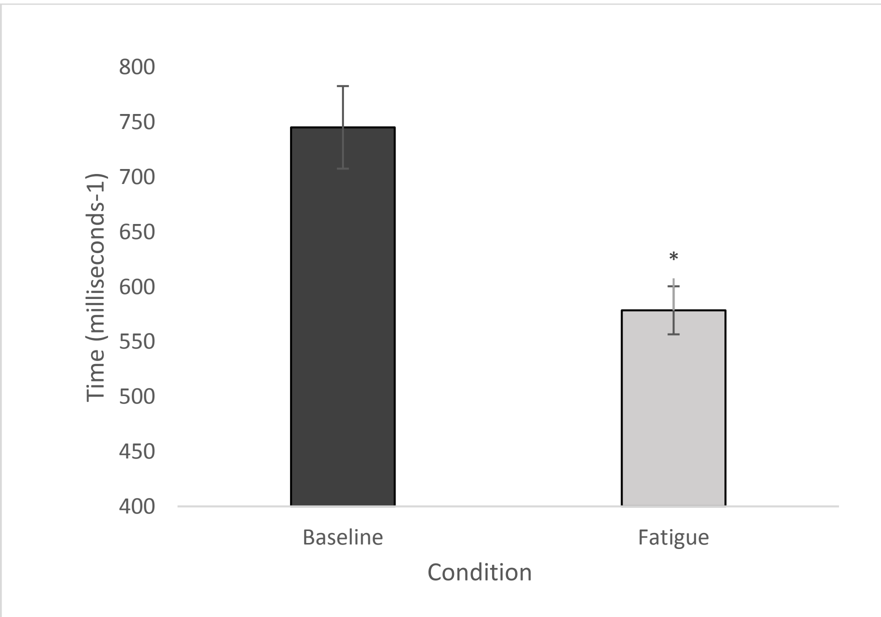

Figure 6.1: Auditory Reaction Time. Baseline vs. fatigue conditions. Data is presented as mean ± standard error; * denotes statistical significance (p <0.05).

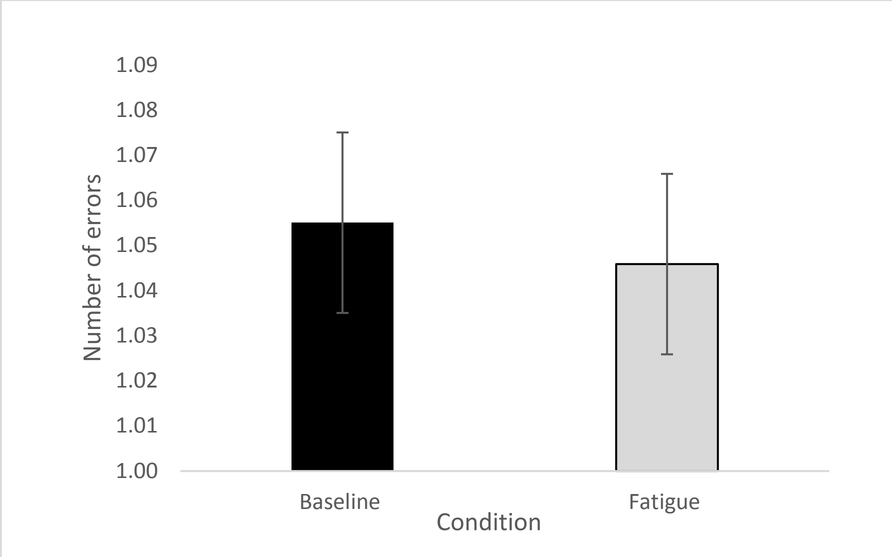

Figure 6.2: Auditory Reaction Time test. Baseline vs. fatigue conditions: Mean number of test performance errors. Data is presented as mean ± standard error.

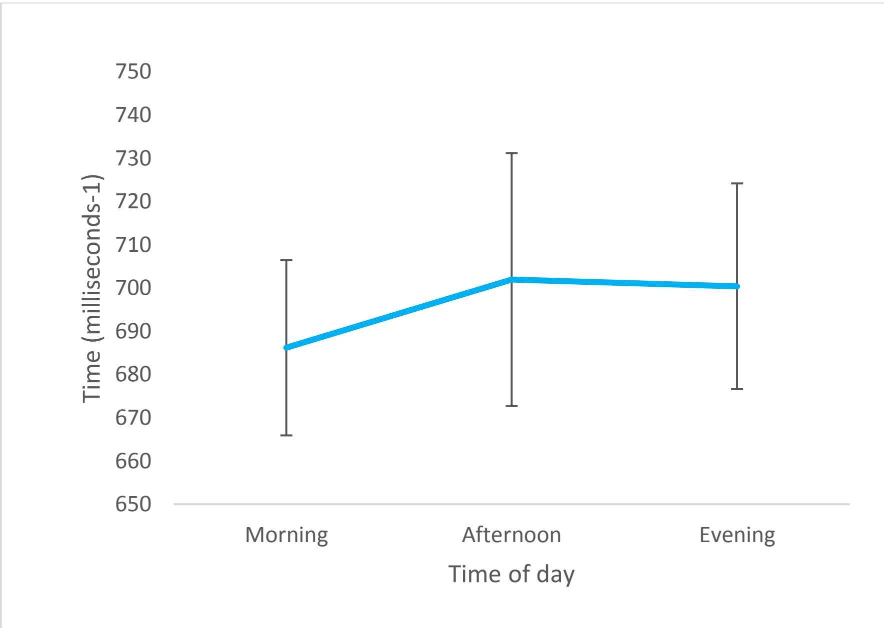

Figure 6.3: Auditory Reaction Time: Diurnal effect on auditory reaction time. Data is presented as mean ± standard error. Morning = 07:00 ± 2h; Afternoon = 14:00 ± 2h; Evening = 19:00 ± 2h.

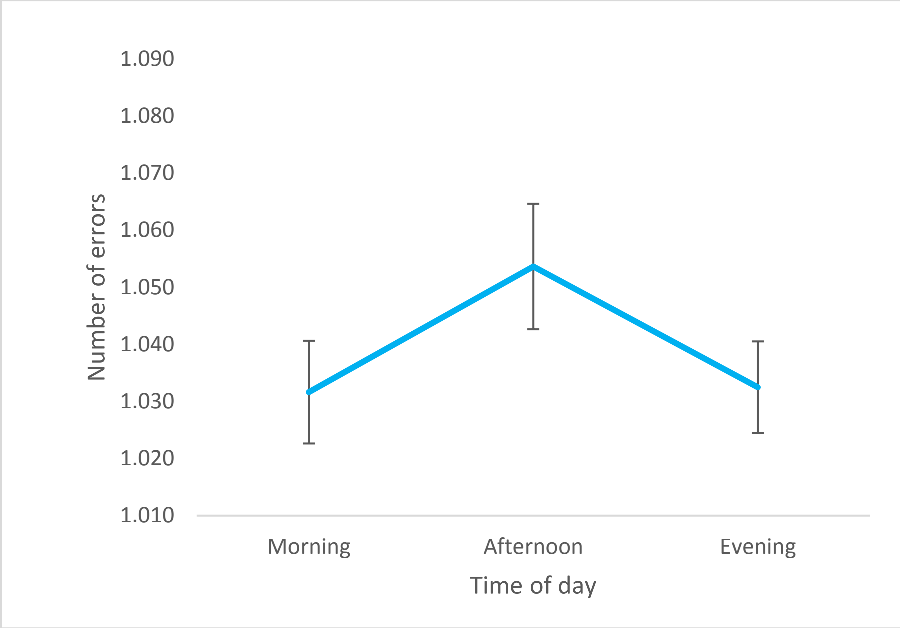

Figure 6.4: Auditory Reaction Time. Diurnal effect on number of test performance errors. Data is presented as mean ± standard error. Morning = 07:00 ± 2h; Afternoon = 14:00 ± 2h; Evening = 19:00 ± 2h.

6.2 Simple Reaction Time

The relationship between simple reaction time at rest and fatigued state is shown in Figure 6.5.

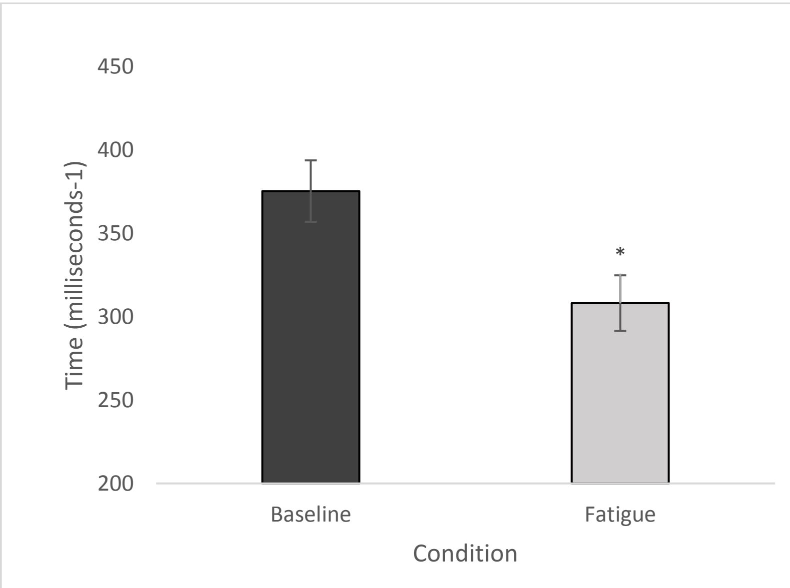

Figure 6.5: Simple Reaction Time. Baseline vs. fatigue conditions. Data is presented as mean ± standard error; * to denote statistical significance ($p < 0.05$).

Fig. 6.6 demonstrates the diurnal effect on simple reaction time. There was a significant difference between baseline and under fatigue conditions ($p < 0.009$). No other significant change was seen.

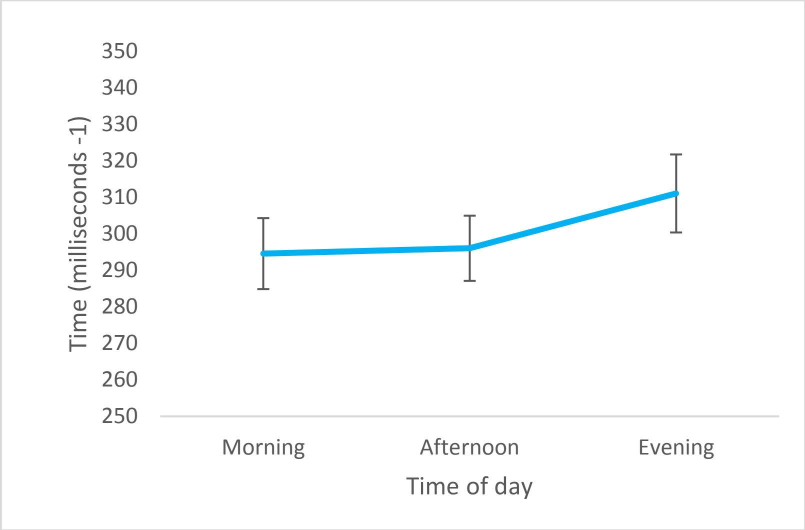

Figure 6.6: Diurnal effect on simple reaction time. Data is presented as mean ± standard error. Morning = 07:00 ± 2h; Afternoon = 14:00 ± 2h; Evening = 19:00 ± 2h.

6.3 Complex Reaction Time

Figures 6.7 and 6.8 illustrate the diurnal and fatiguing effects on complex reaction time. No significant differences were found.

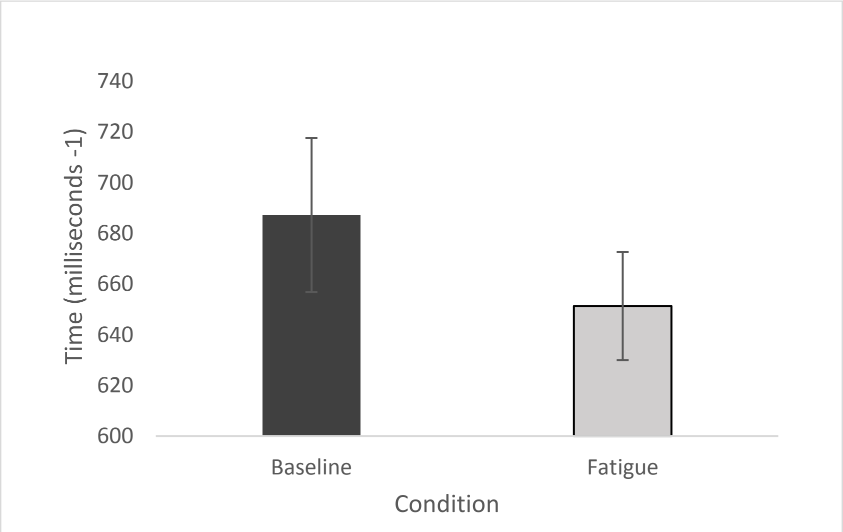

Figure 6.7: Complex Reaction Time. Baseline vs. fatigue conditions. Data is presented as mean ± standard error.

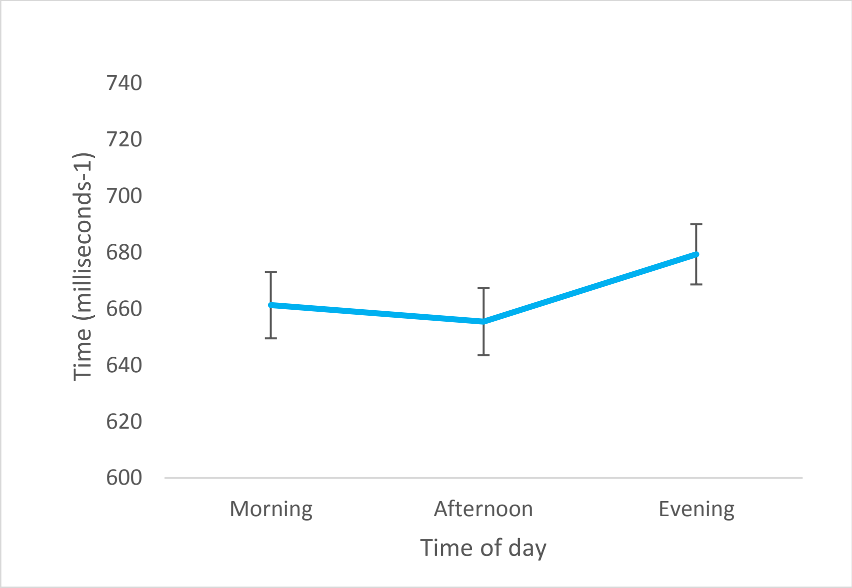

Figure 6.8: Diurnal effect on complex reaction time. Data is presented as mean ± standard error. Morning = 07:00 ± 2h; Afternoon = 14:00 ± 2h; Evening = 19:00 ± 2h.

6.4 Digit-span Backwards

Total mean number of attempts and level reached are illustrated in the figures 6.9-6.12. The mean level reached was significantly higher ($p < 0.038$) during the fatigued conditions. All other values were not significant.

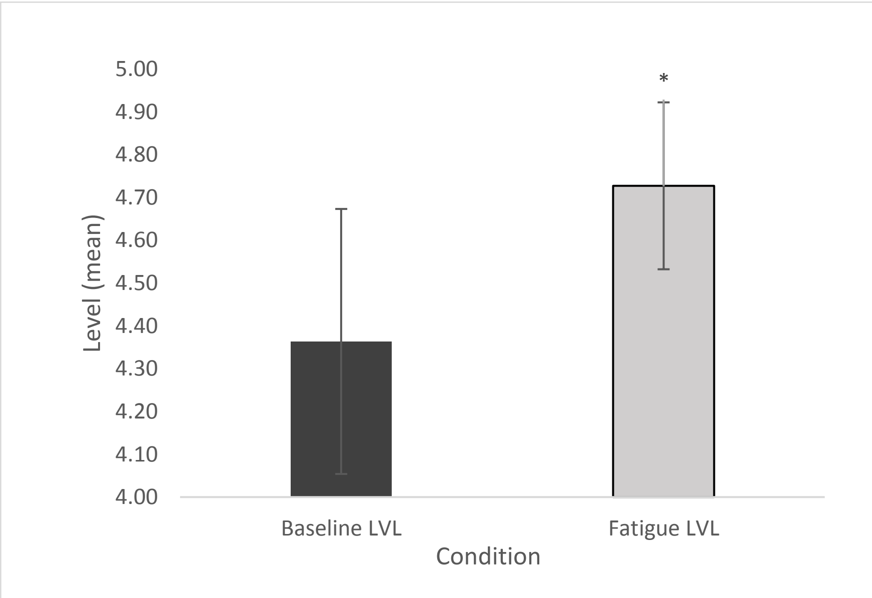

Figure 6.9: Digit-span Backwards. Baseline vs. fatigue conditions: level reached (1-5). Data is presented as mean ± standard error; * denotes statistical significance ($p < 0.05$).

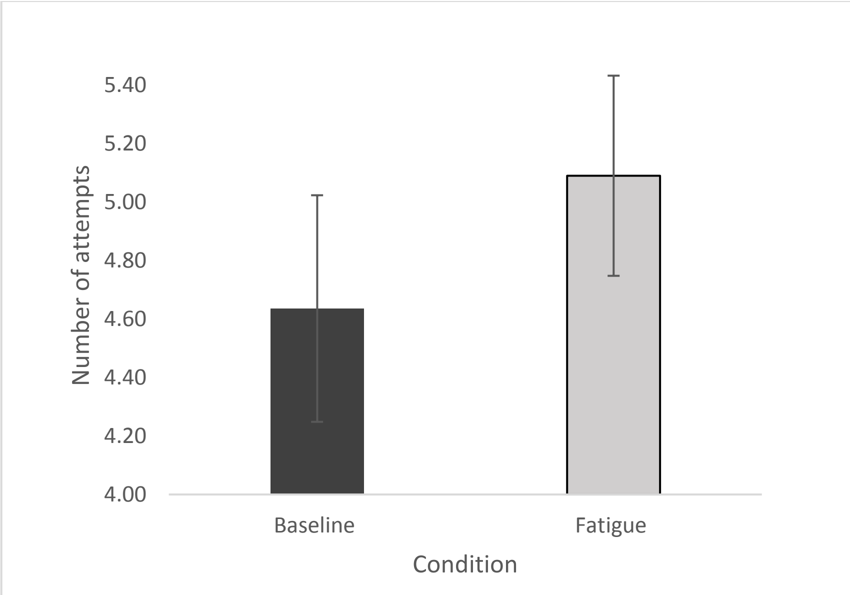

Figure 6.10: Digit-span Backwards. Baseline vs. fatigue conditions: Number of attempts. Data is presented as mean ± standard error.

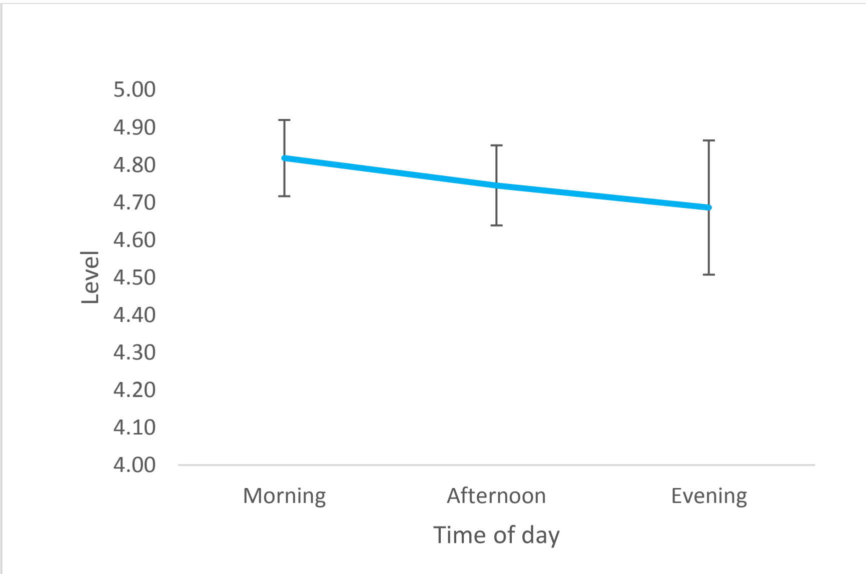

Figure 6.11: Digit-span Backwards. Diurnal effect on level reached (1-5). Data is presented as mean ± standard error. Morning = 07:00 ± 2h; Afternoon = 14:00 ± 2h; Evening = 19:00 ± 2h.

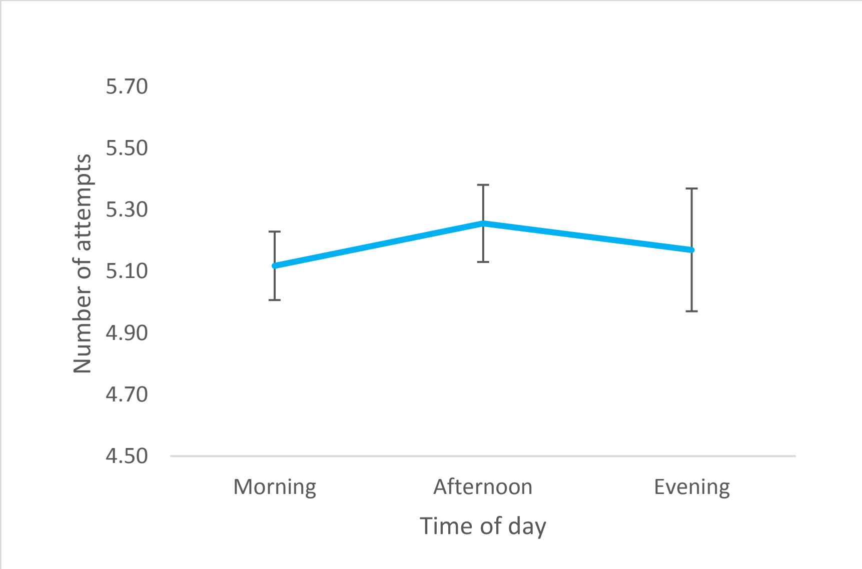

Figure 6.12: Digit-span Backwards. Diurnal effect on number of attempts. Data is presented as mean ± standard error.

Chapter 7. Discussion

Following guidelines of SCAT 3, plus considerations of physical and time parameters a self-administered web-based concussion app was developed that was shown to be reliable and repeatable. Successive repeat assessments including baseline, at rest, and following physical fatigue showed that certain tests were influenced by fatigue which is indicative of sensitivity, but not by diurnal variations. Unique data on the inclusion of an auditory reaction time test, a measure of auditory dysfunction, was sensitive to the effects of cognitive fatigue following physical exertion.

The CAWA developed is unique for its inclusion of a measure of auditory processing reaction time. The results suggest there is a significant change in auditory reaction time (p < 0.05) with fatigue, indicating that auditory dysfunction is a sensitive measure of cognitive and higher brain function and should be included in the assessment for cognitive change following concussion. The processing and integration of multiple sensory inputs simultaneously play a crucial part in an athlete's ability to plan and perform appropriate activities necessary in a dynamic sporting environment (Tapper, Niechwiej-Szwedo, Gonzalez, & Roy, 2015). It is also important to understand how sports may impact dual task information processing capacity as athletes consistently divide their attention between visual and auditory stimulus and reaction in a correct and efficient manner. Pain and Hibbs (2007) illustrated how auditory reaction time in athletes has the fastest reaction-conduction time to the motor cortex, a finding consistent in analogous athletic populations (Shelton & Kumar, 2010), and relative to this current study. Empirical evidence has also linked mTBI and subsequent auditory dysfunction to whiplash in motor vehicle accidents (Atcherson & Steele, 2016); an injury commonly exhibited by collisions in contact sports (Koh et al., 2003). However, investigations considering the impact that head injury has on information processing of auditory inputs for sport-related concussion detection and monitoring is absent. Therefore, the novelty of these findings is providing evidence that auditory processing is vital for inclusion in the assessment of sports-related concussion.

To our knowledge, this is the first study to examine the reliability and repeatability of a digital platform test battery for concussion. In the current study, the effect of fatigue on cognition was controlled by testing the participants using CAWA pre-and-post a maximal graded exercise test (GXT) to volitional exhaustion. Maximal exertion was attained via a treadmill running based protocol, which has been shown to attenuate a limiting effect on specific cognitive functions (Covassin, Weiss, Powell, & Womack, 2007). In the protocol used, exhaustion was measured by the participant identifying a value of 19-20 on the Borg Rate of Perceived Exertion Scale (Borg, 1998), in conjunction with heart rate values identified >95% heart rate maximum. Thus, it was reasonable to propose that our participants would have performed comparatively worse in a physical fatigued state similar to that of a concussion, as reflected by a poor CAWA result. However, this was not observed. In the current study, the GXT resulted in improved test scores for three of the four neurocognitive test measures, despite participants reaching volitional exhaustion. In fact, statistically significant ($p < 0.05$) improvements were observed for the simple reaction time (Figure 6.5), auditory reaction time (Figure 6.1), and the level reached in the digit-span backwards (Figure 6.9) tasks as supported by the paired samples T-test scores, and relatively small effect size (see Table 6.1). Insignificant improvements were also observed for the complex reaction time task. This enhancement of cognitive function with exercise is comparable to that recently demonstrated by Samuel et al. (2017) who found beneficial cognitive effects following maximal intensity exercise. In contrast, Covassin et al., (2007) found a cognitively detrimental effect using a comparable exercise protocol. Although the current study used a similar method to Covassin et al (2007), who observed an opposing and limiting effect on cognition (verbal memory composite scores) it appears the GXT was not sufficient in producing cognitive impairment. It is possible that the exercise acted as a physiological and psychological primer rather than energy and cognitively depleting. It could be argued this was related to the incremental treadmill protocol lasting 10-12-minutes comprising of too little high intensity volume to produce a fatigue-inducing effect resulting in information processing speeds and working memory improvements, as displayed by the current findings. Furthermore, the fact that the participants in the current study improved acuity and reaction time when fatigued for visual tasks, it may be beneficial to look at the fatiguing effects of physical activity in a more realistic situation (i.e., tested in the field) to gauge how sport-specific activity, and concussion, would affect the App sensitivity for cognitive change. In contrast, the sensitivity of the App might have been precise and the test was in fact fatiguing; however, until further investigation, we are unable to clarify. Additionally, in the 2007 study, Covassin et al recruited 102 recreational athletes (men and women), whereas in the current study 11 healthy participants were recruited of various fitness levels. It is possible the comparatively smaller sample size was incapable of detecting clinically relevant differences in the data. Regardless, the results indicate that the CAWA battery is sensitive to the effects of treadmill-based maximal exercise.

Peaks and troughs in performance of cognitively demanding tasks exhibit diurnal variation and characterise our daily functioning. For example, shift workers often suffer from increased sleepiness and subjectively decreased mental performance during night-time shifts (Higuchi, Liu, Yuasa, Maeda, & Motohashi, 2000). Even during the day, diurnal variation exists in the degree of mental aptitude, however, the amount of variation remains uncertain (Higuchi et al., 2000). While previous literature has demonstrated inconsistent findings for diurnal peaks and troughs in cognition as a function of the time of day (Higuchi et al., 2000; Wesensten, Badia, & Harsh, 1990; Wright Jr et al., 2012), the findings from the current study have demonstrated reliability when challenged with diurnal variation. This is supported by the consistently small *Effect Sizes* calculated, and lack of any differences between mornings, afternoon and evening repeated tests over five-days (Table 6.2). All four neuropsychological tests (Simple Reaction Time, Complex Reaction Time, Digit Span Backwards, and Auditory Reaction Time) showed the same general dynamic profile, with individual performances being comparable across the three times of day CAWA was performed. This lack of diurnal variation could be related to the simplicity of the cognitive tasks included in the CAWA. Folkard, Hume, Minors, Waterhouse, & Watson (1985) suggested that simple cognitive tasks are performed at a higher performance levels in the afternoon and evening when compared to the morning; a contrast to the typical ‘afternoon dip’ in cognitive function (Higuchi et al., 2000). However, this finding was challenged by Higuchi et al. (2000), who found a latency ($m.s^{-1}$) at 14:00 for a reaction time task. Nonetheless, in the current study, the value of the diurnal stability lies in the optimal level of sensitivity (i.e., as to not be over-sensitive) of the Web-App to reliably repeat multiple assessments throughout the day. This reliability must not only remain consistent during a lack of hallmark concussion symptomology (visible or otherwise), but also be available for re-testing often enough in the subsequent hours/days to pick up latent worsening of symptoms. Current neuropsychological test batteries are used to classify cognitive degeneration/improvement by means of a one-off examination carried out during or after a sport/game. The ability to reliably repeat concussion assessment during the latent non-linear and ambiguous symptom development illustrated by concussion is vital to understanding the subtleties during the initial and subsequent stages of the injury.

It should also be mentioned that despite diurnal consistency in our results, the data collected from our cohort displayed a mean simple reaction time of 375 $m.s^{-1}$ which fell in the upper range (233 – 397 $m.s^{-1}$) reported in most previous computerised sample reaction time studies (Woods et al., 2015). In fact, our cohort performed marginally slower on all reaction time measures when compared to previous literature. For example, Atan and Akyol (2014) found auditory reaction time ranging between 318 – 259 $m.s^{-1}$ in athletes who were engaged with various sports branches; considerably faster than found in the current study (579 – 745 $m.s^{-1}$). This measurement may vary as a function of the precision of the technological systems or hardware used for testing. According to Neath, Earle, Hallett, & Surprenant (2011) technological hardware delay can inflate true simple reaction times by up to 100 $m.s^{-1}$. This could be related to a delay in the appearance of the stimulus after the software sends the image information. In addition, there is well-known variability with response latency times across tablets and smartphone devices for reaction time assessments (Grant, Honn, Layton, Riedy, & Van Dongen, 2017; Honn, Riedy, & Grant, 2015). For that reason, in the current experiment, we used consistent device platforms and recorded the software detail (device details and operating system), enabling corrections in the data set at a later date, when desired.

7.1 Limitations

It is important to view the results from the current study in the context of its limitations. Firstly, this sample is useful in considering CAWA in an asymptomatic average-to-above average adolescent and young adult population. However, the current data represent preliminary findings on a relatively small cohort and do not generalise outcomes for younger, adolescent and youth athletes, such as those competing at college level or community club level sporting teams. The participants involved in this study were neurologically intact college students, and were classed as healthy active individuals, not athletes, whom may have presented to testing with vastly different motivations and interests. Moreover, as suggested by (Allen & Gfeller, 2011), the variables may not demonstrate the same associations in impaired populations as they do in the normal controlled sample. For example, a larger differentiation in immediate working memory (displayed in the Digit-span Backwards) might be more evident in concussed populations, which is the topic of the next phase of research. However, that is beyond the scope of this present study, as the intention of was to demonstrate the reliability and sensitivity of the app components.

Secondly, the use of a general laboratory-based aerobic running protocol to elicit the fatigue producing effects of physical activity may have been insufficient in causing cognitive impairment evident by the increase in speed ($m.s^{-1}$) across multiple measures (see Table 6.1). The aim of the study was to test the sensitivity of the CAWA (accepted), and the hypothesis that the App is insensitive to fatigue (so as not to confuse fatigue with concussion), was not rejected. Acute high intensity physical exercise has previously been found to lead to a decline in cognitive performance measured immediately following the exercise bout. Bue-Estes et al. (2008) tested college students on selected cognitive variable directly after maximal exercise. The results indicated that maximal exercise could produce both debilitating and facilitating cognitive performance effects depending on the type of function assessed. Moreover, Samuel et al. (2017) describes how gains in executive functions (e.g., working memory, processing speed) can be seen following moderate intensity exercise.

Lastly, variables such as the participant's fitness levels, hydration status and hours of sleep were not controlled in this study over the five days or repeat diurnal testing. The limitation of fitness status should only have a small effect on the results of the study as the purpose was not to determine how fitness level affected neurocognitive performance. However, despite athletes not differing in general cognitive ability, it seems trained individuals can maintain these during physical exercise, especially under high-intensity exercise conditions. It is reasonable to suggest that both athletes and non-athlete's attentional performance would increase during low-moderate intensity exercise due to enhanced arousal and amount of allocable cognitive resource (Hüttermann & Memmert, 2014). As the anaerobic threshold is met, non-trained persons attentional focus would decrease, while an athlete would persist up to a more notable intensity. This provides evidence the participants in our study were generally well trained since they gained acuity. Moreover, both dehydration (Tomporowski, Beasman, Ganio, & Cureton, 2007), and a lack of sleep (Alhola & Polo-Kantola, 2007) are shown to cause prominent deteriorative effects on neurocognitive function yet were not evident in our diurnal results.

7.2 Conclusions

The Concussion Assessment Web-App tool aims to convert the best practice guidelines on concussion in sport into a digital pragmatic format that is accessible for multiple repeat testing, cost-effective, and easy to understand for the individual.

These preliminary findings indicate that the CAWA is a repeatable and sensitive tool for assessing and tracking cognitive change throughout the course of the day. The advantages being offered by the CAWA are the inclusion of auditory testing, availability on a web-based platform, in-built analysis, subtle detection of cognitive change, reliable baseline and repeat assessment, brief running time (<7-minutes), not affected by fatiguing exercise and can be accessed via multiple devices. Because of this, the CAWA has the potential to be useful for both research investigations, and time efficient management of cognitive change. We hope that with further investigations into the psychometric properties of CAWA in various healthy and sports-related settings, we will lead to a more comprehensive understanding of clinical sports-related concussion detection and injury management.

7.3 Future directions

Further research is needed in the development process of the CAWA, particularly field-based testing. Identifying test sensitivity for discrimination of symptom severity and outcome is the next phase of CAWA validity testing. It may aid in clinical evaluation (i.e., Z-scores for risk classification), while understanding the cognitive effects of a more endurance based fatiguing exercise protocol on the reliability and sensitivity of the CAWA would only increase the utility of the web-app as sport concussion App.

As previously discussed, the current study should also be replicated in more diverse populations relevant to the use of these batteries (i.e., in specific and larger concussed and sporting populations). Additional prospective studies comparing post-concussion data to baseline and follow up assessments using the CAWA, will help establish efficacy and utility for detection, and monitoring the effect concussion has on cognitive functioning over time.

Chapter 8. References

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Chapter 9. Appendices

Appendix A: Information Sheet

MASSEY UNIVERSITY

College of Health
School of Sport and Exercise
Massey University
Private Bag 756
Wellington 6140

Concussion risk, detection and prevalence in New Zealand Amateur Rugby: Test-retest reliability of an amateur concussion assessment tool.

INFORMATION SHEET

Thank you for showing an interest in this study. Please read everything below before deciding if you wish to participate. This information sheet will tell you a little more about the study and what we would like you to do.

What is the purpose of the research?
This research is to be conducted through Massey University and is looking at concussion detection in amateur rugby union. The project is being performed by David Sturrock (master's student) supervised by Dr. Sally Lark and Dr. Wyatt page. The purpose of this project is to determine the test-retest reliability of a novel smart phone App designed for assisting in concussion identification. Results from this research will inform the most reliable assessments to perform in subsequent phases of a larger project.

<u>As healthy individuals aged 16-35 we would like to invite you to participate in this research.</u>

Who can take part in this study?
We require you to be aged 16-35 and familiar with using smartphone devices. Unfortunately, you will not be eligible if you have any injury preventing involvement in running, any cardiovascular health risks, suffered from concussive within the past six months, currently suffering from tinnitus, or suffer from chronic migraines. You will be asked to complete a Health History Questionnaire prior to participation to help identify any conditions you may have for inclusion / exclusion from the study.

How long and where will this study take place?
All testing will take place in the Massey University Sport and Exercise research lab located on Wallace Street, Wellington. You will be required to come into the testing facility a total of two times. The days you are required to come in for testing are days 1 for initial testing and 5 days post your first assessment. The first and final assessments will take approximately 40 minutes to complete. Testing sessions will be scheduled around your commitments.

Please note you if you miss a testing session by ± 24 hours, your results will be deemed invalid and you will be withdrawn from the study.

What will happen?
On day one we will ask you to sign informed consent before any testing takes place. This first visit will also include completion of the Health History Questionnaire prior to a practice trial of the App on a smartphone device. Ten minutes after your practice trial you will then perform a baseline assessment with the App. This entire baseline session is expected to take 40 minutes.

The App will ask generic questions aimed to identify a concussion, and ask you to grade the presence and severity of some symptoms. You will then perform interactive tasks that will measure your reaction time to visual and auditory ques, memory, and fine motor skills. Throughout days 1 (following initial assessment), 2, 3, 4, and 5 you are required to perform the App 3 times daily (8am± 1 hour, 2pm± 1 hour, and 8pm ± 1 hour) at your place of residence with accessibility to your personal smartphone.

On the final visit 5 days post baseline assessment you will be required to perform the App again in the Laboratory, which is expected to take 15 minutes.

At 5 days post baseline, you will be required to perform an exercise test on a motorized treadmill prior to completing the App. Before the exercise we will take your blood pressure, and get you to attach a heart rate monitor around your chest. You will then perform a light warm-up on the treadmill for five minutes. After a short recovery, the exercise test will start at your treadmill warm-up speed and increase by 1km.h every two minutes until you decide that can no longer maintain the intensity. We will record heart rate and ask how difficult you are finding the exercise at the end of each stage. Once you have finished the test you will be given five minutes rest, and then asked to complete the App. This session is expected to take 40 minutes to complete.

Are there any risks?
Just like any other mode of exercise there is the risk of straining a muscle when running. However, these risks are minimized in this study by allowing a five minute warm-up, and starting the exercise test from a speed that you believe is light. The gradual increase in intensity will allow your body to become accustomed to each exercise stage.

What will happen to this information?
All physical and Health History data will be kept by the researchers. All data collected via the App will upload to a secure Cloud database for access by the researchers only. Any data presented will be on a group basis only. **All information gathered throughout this research project will remain anonymous and strictly confidential**. We may use the data that we collect in publications or during presentations, but no one will be able to tell which data yours is. At the end of the project, a summary of findings will be sent to you via email within six months from the completion of data collection.

You are under no obligation to accept this invitation. You have the right to:

- decline to answer any particular question;

- withdraw from the study at any point of time until completion of final day of testing;
- ask any questions about the study at any time during participation;
- provide information on the understanding that your name will not be used unless you give permission to the researcher;
- be given access to a summary of the project findings when it is concluded.

Project Contacts

David Sturrock	Email: dsturrock17@gmail.ac.nz	ph: 027 308 3889
Dr. Sally Lark	Email: s.lark@massey.ac.nz	ph: 04 801 5799 ext 63497
Dr. Wyatt Page	Email: w.page@massey.ac.nz	

If you have any queries relating to this research project then feel free to contact the researcher and/or supervisors.

This project has been reviewed and approved by the Massey University Human Ethics Committee: XXXXXXXXXXX. If you have any concerns about the conduct of this research, please contact XXXXXXXXXXX, Chair, and Massey University Human Ethics Committee: XXXXXXXXX, telephone 04 801 5799 x 63487, email humanethicsoutha@massey.ac.nz.

Compensation for Injury

If physical injury results from your participation in this study, you should visit a treatment provider to make a claim to ACC as soon as possible. ACC cover and entitlements are not automatic and your claim will be assessed by ACC in accordance with the Accident Compensation Act 2001. If your claim is accepted, ACC must inform you of your entitlements, and must help you access those entitlements. Entitlements may include, but not be limited to, treatment costs, travel costs for rehabilitation, loss of earnings, and/or lump sum for permanent impairment. Compensation for mental trauma may also be included, but only if this is incurred as a result of physical injury.

If your ACC claim is not accepted you should immediately contact the researcher. The researcher will initiate processes to ensure you receive compensation equivalent to that to which you would have been entitled had ACC accepted your claim.

Appendix B: Consent form

MASSEY UNIVERSITY

College of Health
School of Sport and Exercise
Massey University
Private Bag 756
Wellington 6140

Concussion risk, detection and prevalence in New Zealand Amateur Rugby: Test-retest reliability of the amateur concussion assessment tool.

PARTICIPANT CONSENT FORM - INDIVIDUAL

I have read the Information Sheet and have had the details of the study explained to me. My questions have been answered to my satisfaction, and I understand that I may ask further questions at any time.

I agree to participate in this study under the conditions set out in the Information Sheet.

Signature: .... **Date:** ....

Full Name - printed ....

Appendix C: Health screening questionnaire

MASSEY UNIVERSITY

College of Health
School of Sport and Exercise
Massey University
Private Bag 756
Wellington 6140

Health History Questionnaire

NAME____
First M.I Last

AGE ________ SEX ________

If you are planning on participating in this research we need to get a gauge on your heath history, and suitability to partake in the exercise test. Please answer the following questions as honestly and accurately as possible by checking YES or NO.

	YES	NO
Has your doctor ever said that you have a heart condition <u>and</u> that you should only do physical activity recommended by a doctor?	□	□
Do you feel pain in your chest when doing physical activity?	□	□
In the past month, have you had chest pain while not doing physical activity?	□	□
Do you lose your balance because of dizziness, or do you ever lose consciousness?	□	□
Is your doctor currently prescribing any medication for blood pressure or a heart condition?	□	□
Do you have diabetes or a thyroid issue?	□	□
Are there any reasons why you should not do physical activity?	□	□

Do you currently smoke? □ YES □ NO **Have you ever quit smoking?** □ YES □ NO

Do you suffer from frequent migraines/headaches? □ YES □ NO

Are you suffering from any neck/back/shoulder pain? □ YES □ NO

Are you currently suffering from tinnitus? □ YES □ NO

Have you ever suffered a concussion? ☐ YES ☐ NO

If yes: How many? ____________

How many months ago was your last one? - ____________

Are you still suffering symptoms? ☐ YES ☐ NO

Do you have any current injury? ☐ YES ☐ NO

Please detail injury (include location of injury & any activities that may aggravate injury)

____

____

____

____

____

Do you engage in regular physical activity: ☐ YES ☐ NO

How often (hours per week)

What kind of exercise do you perform? Cardio training ☐ YES ☐ NO ______________

Resistance training ☐ YES ☐ NO ______________

Sport ☐ YES ☐ NO ______________

What sports do you play? ____________________________

Have you ever had:

YES	**NO**		When	How
☐	☐	Previous neck/shoulder injury? ______________________________		
☐	☐	Numbness or tingling in upper extremity, neck or back? ______________________		

Signed ______________________________________

Date ____

Appendix D: Sport Concussion Assessment Tool (5th Edition)

BJSM Online First, published on April 26, 2017 as 10.1136/bjsports-2017-097506SCAT5
To download a clean version of the SCAT tools please visit the journal online (http://dx.doi.org/10.1136/bjsports-2017-097506SCAT5)

SCAT5.©

SPORT CONCUSSION ASSESSMENT TOOL — 5TH EDITION
DEVELOPED BY THE CONCUSSION IN SPORT GROUP
FOR USE BY MEDICAL PROFESSIONALS ONLY

supported by

FIFA

Patient details

Name: ____________________

DOB: ____________________

Address: ____________________

ID number: ____________________

Examiner: ____________________

Date of Injury: ____________________ Time: ____________________

WHAT IS THE SCAT5?

The SCAT5 is a standardized tool for evaluating concussions designed for use by physicians and licensed healthcare professionals[1]. The SCAT5 cannot be performed correctly in less than 10 minutes.

If you are not a physician or licensed healthcare professional, please use the Concussion Recognition Tool 5 (CRT5). The SCAT5 is to be used for evaluating athletes aged 13 years and older. For children aged 12 years or younger, please use the Child SCAT5.

Preseason SCAT5 baseline testing can be useful for interpreting post-injury test scores, but is not required for that purpose. Detailed instructions for use of the SCAT5 are provided on page 7. Please read through these instructions carefully before testing the athlete. Brief verbal instructions for each test are given in italics. The only equipment required for the tester is a watch or timer.

This tool may be freely copied in its current form for distribution to individuals, teams, groups and organizations. It should not be altered in any way, re-branded or sold for commercial gain. Any revision, translation or reproduction in a digital form requires specific approval by the Concussion in Sport Group.

Recognise and Remove

A head impact by either a direct blow or indirect transmission of force can be associated with a serious and potentially fatal brain injury. If there are significant concerns, including any of the red flags listed in Box 1, then activation of emergency procedures and urgent transport to the nearest hospital should be arranged.

Key points

- Any athlete with suspected concussion should be REMOVED FROM PLAY, medically assessed and monitored for deterioration. No athlete diagnosed with concussion should be returned to play on the day of injury.
- If an athlete is suspected of having a concussion and medical personnel are not immediately available, the athlete should be referred to a medical facility for urgent assessment.
- Athletes with suspected concussion should not drink alcohol, use recreational drugs and should not drive a motor vehicle until cleared to do so by a medical professional.
- Concussion signs and symptoms evolve over time and it is important to consider repeat evaluation in the assessment of concussion.
- The diagnosis of a concussion is a clinical judgment, made by a medical professional. The SCAT5 should NOT be used by itself to make, or exclude, the diagnosis of concussion. An athlete may have a concussion even if their SCAT5 is "normal".

Remember:

- The basic principles of first aid (danger, response, airway, breathing, circulation) should be followed.
- Do not attempt to move the athlete (other than that required for airway management) unless trained to do so.
- Assessment for a spinal cord injury is a critical part of the initial on-field assessment.
- Do not remove a helmet or any other equipment unless trained to do so safely.

Davis GA, *et al. Br J Sports Med* 2017;0:1–8. doi:10.1136/bjsports-2017-097506SCAT5 1

1

IMMEDIATE OR ON-FIELD ASSESSMENT

The following elements should be assessed for all athletes who are suspected of having a concussion prior to proceeding to the neurocognitive assessment and ideally should be done on-field after the first first aid / emergency care priorities are completed.

If any of the "Red Flags" or observable signs are noted after a direct or indirect blow to the head, the athlete should be immediately and safely removed from participation and evaluated by a physician or licensed healthcare professional.

Consideration of transportation to a medical facility should be at the discretion of the physician or licensed healthcare professional.

The GCS is important as a standard measure for all patients and can be done serially if necessary in the event of deterioration in conscious state. The Maddocks questions and cervical spine exam are critical steps of the immediate assessment; however, these do not need to be done serially.

STEP 1: RED FLAGS

RED FLAGS:

- **Neck pain or tenderness**
- **Double vision**
- **Weakness or tingling/ burning in arms or legs**
- **Severe or increasing headache**
- **Seizure or convulsion**
- **Loss of consciousness**
- **Deteriorating conscious state**
- **Vomiting**
- **Increasingly restless, agitated or combative**

STEP 2: OBSERVABLE SIGNS

Witnessed ☐ Observed on Video ☐

Lying motionless on the playing surface	Y	N
Balance / gait difficulties / motor incoordination: stumbling, slow / laboured movements	Y	N
Disorientation or confusion, or an inability to respond appropriately to questions	Y	N
Blank or vacant look	Y	N
Facial injury after head trauma	Y	N

STEP 3: MEMORY ASSESSMENT MADDOCKS QUESTIONS[2]

"I am going to ask you a few questions, please listen carefully and give your best effort. First, tell me what happened?"

Mark Y for correct answer / N for incorrect

What venue are we at today?	Y	N
Which half is it now?	Y	N
Who scored last in this match?	Y	N
What team did you play last week / game?	Y	N
Did your team win the last game?	Y	N

Note: Appropriate sport-specific questions may be substituted.

Name: ____________________

DOB: ____________________

Address: ____________________

ID number: ____________________

Examiner: ____________________

Date: ____________________

STEP 4: EXAMINATION GLASGOW COMA SCALE (GCS)[3]

Time of assessment			
Date of assessment			
Best eye response (E)			
No eye opening	1	1	1
Eye opening in response to pain	2	2	2
Eye opening to speech	3	3	3
Eyes opening spontaneously	4	4	4
Best verbal response (V)			
No verbal response	1	1	1
Incomprehensible sounds	2	2	2
Inappropriate words	3	3	3
Confused	4	4	4
Oriented	5	5	5
Best motor response (M)			
No motor response	1	1	1
Extension to pain	2	2	2
Abnormal flexion to pain	3	3	3
Flexion / Withdrawal to pain	4	4	4
Localizes to pain	5	5	5
Obeys commands	6	6	6
Glasgow Coma score (E + V + M)			

CERVICAL SPINE ASSESSMENT

Does the athlete report that their neck is pain free at rest?	Y	N
If there is NO neck pain at rest, does the athlete have a full range of ACTIVE pain free movement?	Y	N
Is the limb strength and sensation normal?	Y	N

In a patient who is not lucid or fully conscious, a cervical spine injury should be assumed until proven otherwise.

Davis GA, et al. Br J Sports Med 2017;0:1–8. doi:10.1136/bjsports-2017-097506SCAT5

OFFICE OR OFF-FIELD ASSESSMENT

Please note that the neurocognitive assessment should be done in a distraction-free environment with the athlete in a resting state.

STEP 1: ATHLETE BACKGROUND

Sport / team / school: ____________________

Date / time of injury: ____________________

Years of education completed: ____________________

Age: ____________________

Gender: M / F / Other

Dominant hand: left / neither / right

How many diagnosed concussions has the athlete had in the past?: ____________________

When was the most recent concussion?: ____________________

How long was the recovery (time to being cleared to play) from the most recent concussion?: ____________________ (days)

Has the athlete ever been:

Hospitalized for a head injury?	Yes	No
Diagnosed / treated for headache disorder or migraines?	Yes	No
Diagnosed with a learning disability / dyslexia?	Yes	No
Diagnosed with ADD / ADHD?	Yes	No
Diagnosed with depression, anxiety or other psychiatric disorder?	Yes	No

Current medications? If yes, please list:

____

____

____

____

____

____

Name: ____________________

DOB: ____________________

Address: ____________________

ID number: ____________________

Examiner: ____________________

Date: ____________________

2

STEP 2: SYMPTOM EVALUATION

The athlete should be given the symptom form and asked to read this instruction paragraph out loud then complete the symptom scale. For the baseline assessment, the athlete should rate his/her symptoms based on how he/she typically feels and for the post injury assessment the athlete should rate their symptoms at this point in time.

Please Check: ☐ **Baseline** ☐ **Post-Injury**

Please hand the form to the athlete

	none	mild		moderate		severe	
Headache	0	1	2	3	4	5	6
"Pressure in head"	0	1	2	3	4	5	6
Neck Pain	0	1	2	3	4	5	6
Nausea or vomiting	0	1	2	3	4	5	6
Dizziness	0	1	2	3	4	5	6
Blurred vision	0	1	2	3	4	5	6
Balance problems	0	1	2	3	4	5	6
Sensitivity to light	0	1	2	3	4	5	6
Sensitivity to noise	0	1	2	3	4	5	6
Feeling slowed down	0	1	2	3	4	5	6
Feeling like "in a fog"	0	1	2	3	4	5	6
"Don't feel right"	0	1	2	3	4	5	6
Difficulty concentrating	0	1	2	3	4	5	6
Difficulty remembering	0	1	2	3	4	5	6
Fatigue or low energy	0	1	2	3	4	5	6
Confusion	0	1	2	3	4	5	6
Drowsiness	0	1	2	3	4	5	6
More emotional	0	1	2	3	4	5	6
Irritability	0	1	2	3	4	5	6
Sadness	0	1	2	3	4	5	6
Nervous or Anxious	0	1	2	3	4	5	6
Trouble falling asleep (if applicable)	0	1	2	3	4	5	6

Total number of symptoms:	of 22
Symptom severity score:	of 132
Do your symptoms get worse with physical activity?	Y N
Do your symptoms get worse with mental activity?	Y N
If 100% is feeling perfectly normal, what percent of normal do you feel?	

If not 100%, why?

____

____

____

Please hand form back to examiner

3

STEP 3: COGNITIVE SCREENING

Standardised Assessment of Concussion (SAC)[4]

Name: ____________________
DOB: ____________________
Address: ____________________
ID number: ____________________
Examiner: ____________________
Date: ____________________

ORIENTATION

What month is it?	0	1
What is the date today?	0	1
What is the day of the week?	0	1
What year is it?	0	1
What time is it right now? (within 1 hour)	0	1
Orientation score		of 5

IMMEDIATE MEMORY

The Immediate Memory component can be completed using the traditional 5-word per trial list or optionally using 10-words per trial to minimise any ceiling effect. All 3 trials must be administered irrespective of the number correct on the first trial. Administer at the rate of one word per second.

Please choose EITHER the 5 or 10 word list groups and circle the specific word list chosen for this test.

I am going to test your memory. I will read you a list of words and when I am done, repeat back as many words as you can remember, in any order. For Trials 2 & 3: I am going to repeat the same list again. Repeat back as many words as you can remember in any order, even if you said the word before.

List	Alternate 5 word lists					Score (of 5) Trial 1	Trial 2	Trial 3
A	Finger	Penny	Blanket	Lemon	Insect			
B	Candle	Paper	Sugar	Sandwich	Wagon			
C	Baby	Monkey	Perfume	Sunset	Iron			
D	Elbow	Apple	Carpet	Saddle	Bubble			
E	Jacket	Arrow	Pepper	Cotton	Movie			
F	Dollar	Honey	Mirror	Saddle	Anchor			
					Immediate Memory Score			of 15
					Time that last trial was completed			

List	Alternate 10 word lists					Score (of 10) Trial 1	Trial 2	Trial 3
G	Finger	Penny	Blanket	Lemon	Insect			
	Candle	Paper	Sugar	Sandwich	Wagon			
H	Baby	Monkey	Perfume	Sunset	Iron			
	Elbow	Apple	Carpet	Saddle	Bubble			
I	Jacket	Arrow	Pepper	Cotton	Movie			
	Dollar	Honey	Mirror	Saddle	Anchor			
					Immediate Memory Score			of 30
					Time that last trial was completed			

CONCENTRATION

DIGITS BACKWARDS

Please circle the Digit list chosen (A, B, C, D, E, F). Administer at the rate of one digit per second reading DOWN the selected column.

I am going to read a string of numbers and when I am done, you repeat them back to me in reverse order of how I read them to you. For example, if I say 7-1-9, you would say 9-1-7.

Concentration Number Lists (circle one)					
List A	List B	List C			
4-9-3	5-2-6	1-4-2	Y	N	0
6-2-9	4-1-5	6-5-8	Y	N	1
3-8-1-4	1-7-9-5	6-8-3-1	Y	N	0
3-2-7-9	4-9-6-8	3-4-8-1	Y	N	1
6-2-9-7-1	4-8-5-2-7	4-9-1-5-3	Y	N	0
1-5-2-8-6	6-1-8-4-3	6-8-2-5-1	Y	N	1
7-1-8-4-6-2	8-3-1-9-6-4	3-7-6-5-1-9	Y	N	0
5-3-9-1-4-8	7-2-4-8-5-6	9-2-6-5-1-4	Y	N	1
List D	List E	List F			
7-8-2	3-8-2	2-7-1	Y	N	0
9-2-6	5-1-8	4-7-9	Y	N	1
4-1-8-3	2-7-9-3	1-6-8-3	Y	N	0
9-7-2-3	2-1-6-9	3-9-2-4	Y	N	1
1-7-9-2-6	4-1-8-6-9	2-4-7-5-8	Y	N	0
4-1-7-5-2	9-4-1-7-5	8-3-9-6-4	Y	N	1
2-6-4-8-1-7	6-9-7-3-8-2	5-8-6-2-4-9	Y	N	0
8-4-1-9-3-5	4-2-7-9-3-8	3-1-7-8-2-6	Y	N	1
		Digits Score:			of 4

MONTHS IN REVERSE ORDER

Now tell me the months of the year in reverse order. Start with the last month and go backward. So you'll say December, November. Go ahead.

Dec - Nov - Oct - Sept - Aug - Jul - Jun - May - Apr - Mar - Feb - Jan	0	1
Months Score		of 1
Concentration Total Score (Digits + Months)		of 5

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STEP 4: NEUROLOGICAL SCREEN

See the instruction sheet (page 7) for details of test administration and scoring of the tests.

Can the patient read aloud (e.g. symptom check-list) and follow instructions without difficulty?	Y	N
Does the patient have a full range of pain-free PASSIVE cervical spine movement?	Y	N
Without moving their head or neck, can the patient look side-to-side and up-and-down without double vision?	Y	N
Can the patient perform the finger nose coordination test normally?	Y	N
Can the patient perform tandem gait normally?	Y	N

BALANCE EXAMINATION

Modified Balance Error Scoring System (mBESS) testing[5]

Which foot was tested (i.e. which is the non-dominant foot) ☐ Left ☐ Right

Testing surface (hard floor, field, etc.) ____________

Footwear (shoes, barefoot, braces, tape, etc.) ____________

Condition	Errors
Double leg stance	of 10
Single leg stance (non-dominant foot)	of 10
Tandem stance (non-dominant foot at the back)	of 10
Total Errors	of 30

Name: ____________

DOB: ____________

Address: ____________

ID number: ____________

Examiner: ____________

Date: ____________

STEP 5: DELAYED RECALL:

The delayed recall should be performed after 5 minutes have elapsed since the end of the Immediate Recall section. Score 1 pt. for each correct response.

Do you remember that list of words I read a few times earlier? Tell me as many words from the list as you can remember in any order.

Time Started ____________

Please record each word correctly recalled. Total score equals number of words recalled.

____

____

____

Total number of words recalled accurately: of 5 or of 10

STEP 6: DECISION

Domain	Date & time of assessment:		
Symptom number (of 22)			
Symptom severity score (of 132)			
Orientation (of 5)			
Immediate memory	of 15 of 30	of 15 of 30	of 15 of 30
Concentration (of 5)			
Neuro exam	Normal Abnormal	Normal Abnormal	Normal Abnormal
Balance errors (of 30)			
Delayed Recall	of 5 of 10	of 5 of 10	of 5 of 10

Date and time of injury: ____________

If the athlete is known to you prior to their injury, are they different from their usual self?
☐ Yes ☐ No ☐ Unsure ☐ Not Applicable
(If different, describe why in the clinical notes section)

Concussion Diagnosed?
☐ Yes ☐ No ☐ Unsure ☐ Not Applicable

If re-testing, has the athlete improved?
☐ Yes ☐ No ☐ Unsure ☐ Not Applicable

I am a physician or licensed healthcare professional and I have personally administered or supervised the administration of this SCAT5.

Signature: ____________

Name: ____________

Title: ____________

Registration number (if applicable): ____________

Date: ____________

SCORING ON THE SCAT5 SHOULD NOT BE USED AS A STAND-ALONE METHOD TO DIAGNOSE CONCUSSION, MEASURE RECOVERY OR MAKE DECISIONS ABOUT AN ATHLETE'S READINESS TO RETURN TO COMPETITION AFTER CONCUSSION.

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CLINICAL NOTES:

Name: ____________
DOB: ____________
Address: ____________
ID number: ____________
Examiner: ____________
Date: ____________

CONCUSSION INJURY ADVICE

(To be given to the person monitoring the concussed athlete)

This patient has received an injury to the head. A careful medical examination has been carried out and no sign of any serious complications has been found. Recovery time is variable across individuals and the patient will need monitoring for a further period by a responsible adult. Your treating physician will provide guidance as to this timeframe.

If you notice any change in behaviour, vomiting, worsening headache, double vision or excessive drowsiness, please telephone your doctor or the nearest hospital emergency department immediately.

Other important points:

Initial rest: Limit physical activity to routine daily activities (avoid exercise, training, sports) and limit activities such as school, work, and screen time to a level that does not worsen symptoms.

1) Avoid alcohol

2) Avoid prescription or non-prescription drugs without medical supervision. Specifically:

   a) Avoid sleeping tablets

   b) Do not use aspirin, anti-inflammatory medication or stronger pain medications such as narcotics

3) Do not drive until cleared by a healthcare professional.

4) Return to play/sport requires clearance by a healthcare professional.

Clinic phone number: ____________

Patient's name: ____________

Date / time of injury: ____________

Date / time of medical review: ____________

Healthcare Provider: ____________

Contact details or stamp

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INSTRUCTIONS

Words in *Italics* throughout the SCAT5 are the instructions given to the athlete by the clinician

Symptom Scale

The time frame for symptoms should be based on the type of test being administered. At baseline it is advantageous to assess how an athlete "typically" feels whereas during the acute/post-acute stage it is best to ask how the athlete feels at the time of testing.

The symptom scale should be completed by the athlete, not by the examiner. In situations where the symptom scale is being completed after exercise, it should be done in a resting state, generally by approximating his/her resting heart rate.

For total number of symptoms, maximum possible is 22 except immediately post injury, if sleep item is omitted, which then creates a maximum of 21.

For Symptom severity score, add all scores in table, maximum possible is 22 x 6 = 132, except immediately post injury if sleep item is omitted, which then creates a maximum of 21x6=126.

Immediate Memory

The Immediate Memory component can be completed using the traditional 5-word per trial list or, optionally, using 10-words per trial. The literature suggests that the Immediate Memory has a notable ceiling effect when a 5-word list is used. In settings where this ceiling is prominent, the examiner may wish to make the task more difficult by incorporating two 5–word groups for a total of 10 words per trial. In this case, the maximum score per trial is 10 with a total trial maximum of 30.

Choose one of the word lists (either 5 or 10). Then perform 3 trials of immediate memory using this list.

Complete all 3 trials regardless of score on previous trials.

"I am going to test your memory. I will read you a list of words and when I am done, repeat back as many words as you can remember, in any order." The words must be read at a rate of one word per second.

Trials 2 & 3 MUST be completed regardless of score on trial 1 & 2.

Trials 2 & 3:

"I am going to repeat the same list again. Repeat back as many words as you can remember in any order, even if you said the word before."

Score 1 pt. for each correct response. Total score equals sum across all 3 trials. Do NOT inform the athlete that delayed recall will be tested.

Concentration

Digits backward

Choose one column of digits from lists A, B, C, D, E or F and administer those digits as follows:

Say: "I am going to read a string of numbers and when I am done, you repeat them back to me in reverse order of how I read them to you. For example, if I say 7-1-9, you would say 9-1-7."

Begin with first 3 digit string.

If correct, circle "Y" for correct and go to next string length. If incorrect, circle "N" for the first string length and read trial 2 in the same string length. One point possible for each string length. Stop after incorrect on both trials (2 N's) in a string length. The digits should be read at the rate of one per second.

Months in reverse order

"Now tell me the months of the year in reverse order. Start with the last month and go backward. So you'll say December, November ... Go ahead"

1 pt. for entire sequence correct

Delayed Recall

The delayed recall should be performed after 5 minutes have elapsed since the end of the Immediate Recall section.

"Do you remember that list of words I read a few times earlier? Tell me as many words from the list as you can remember in any order."

Score 1 pt. for each correct response

Modified Balance Error Scoring System (mBESS)[5] testing

This balance testing is based on a modified version of the Balance Error Scoring System (BESS)[5]. A timing device is required for this testing.

Each of 20-second trial/stance is scored by counting the number of errors. The examiner will begin counting errors only after the athlete has assumed the proper start position. The modified BESS is calculated by adding one error point for each error during the three 20-second tests. The maximum number of errors for any single condition is 10. If the athlete commits multiple errors simultaneously, only one error is recorded but the athlete should quickly return to the testing position, and counting should resume once the athlete is set. Athletes that are unable to maintain the testing procedure for a minimum of five seconds at the start are assigned the highest possible score, ten, for that testing condition.

OPTION: For further assessment, the same 3 stances can be performed on a surface of medium density foam (e.g., approximately 50cm x 40cm x 6cm).

Balance testing – types of errors

1. Hands lifted off iliac crest
2. Opening eyes
3. Step, stumble, or fall
4. Moving hip into > 30 degrees abduction
5. Lifting forefoot or heel
6. Remaining out of test position > 5 sec

"I am now going to test your balance. Please take your shoes off (if applicable), roll up your pant legs above ankle (if applicable), and remove any ankle taping (if applicable). This test will consist of three twenty second tests with different stances."

(a) Double leg stance:

"The first stance is standing with your feet together with your hands on your hips and with your eyes closed. You should try to maintain stability in that position for 20 seconds. I will be counting the number of times you move out of this position. I will start timing when you are set and have closed your eyes."

(b) Single leg stance:

"If you were to kick a ball, which foot would you use? [This will be the dominant foot] *Now stand on your non-dominant foot. The dominant leg should be held in approximately 30 degrees of hip flexion and 45 degrees of knee flexion. Again, you should try to maintain stability for 20 seconds with your hands on your hips and your eyes closed. I will be counting the number of times you move out of this position. If you stumble out of this position, open your eyes and return to the start position and continue balancing. I will start timing when you are set and have closed your eyes."*

(c) Tandem stance:

"Now stand heel-to-toe with your non-dominant foot in back. Your weight should be evenly distributed across both feet. Again, you should try to maintain stability for 20 seconds with your hands on your hips and your eyes closed. I will be counting the number of times you move out of this position. If you stumble out of this position, open your eyes and return to the start position and continue balancing. I will start timing when you are set and have closed your eyes."

Tandem Gait

Participants are instructed to stand with their feet together behind a starting line (the test is best done with footwear removed). Then, they walk in a forward direction as quickly and as accurately as possible along a 38mm wide (sports tape), 3 metre line with an alternate foot heel-to-toe gait ensuring that they approximate their heel and toe on each step. Once they cross the end of the 3m line, they turn 180 degrees and return to the starting point using the same gait. Athletes fail the test if they step off the line, have a separation between their heel and toe, or if they touch or grab the examiner or an object.

Finger to Nose

"I am going to test your coordination now. Please sit comfortably on the chair with your eyes open and your arm (either right or left) outstretched (shoulder flexed to 90 degrees and elbow and fingers extended), pointing in front of you. When I give a start signal, I would like you to perform five successive finger to nose repetitions using your index finger to touch the tip of the nose, and then return to the starting position, as quickly and as accurately as possible."

References

1. McCrory et al. Consensus Statement On Concussion In Sport – The 5th International Conference On Concussion In Sport Held In Berlin, October 2016. British Journal of Sports Medicine 2017 (available at www.bjsm.bmj.com)
2. Maddocks, DL; Dicker, GD; Saling, MM. The assessment of orientation following concussion in athletes. Clinical Journal of Sport Medicine 1995; 5: 32-33
3. Jennett, B., Bond, M. Assessment of outcome after severe brain damage: a practical scale. Lancet 1975; i: 480-484
4. McCrea M. Standardized mental status testing of acute concussion. Clinical Journal of Sport Medicine. 2001; 11: 176-181
5. Guskiewicz KM. Assessment of postural stability following sport-related concussion. Current Sports Medicine Reports. 2003; 2: 24-30

CONCUSSION INFORMATION

Any athlete suspected of having a concussion should be removed from play and seek medical evaluation.

Signs to watch for

Problems could arise over the first 24-48 hours. The athlete should not be left alone and must go to a hospital at once if they experience:

- Worsening headache
- Drowsiness or inability to be awakened
- Inability to recognize people or places
- Repeated vomiting
- Unusual behaviour or confusion or irritable
- Seizures (arms and legs jerk uncontrollably)
- Weakness or numbness in arms or legs
- Unsteadiness on their feet.
- Slurred speech

Consult your physician or licensed healthcare professional after a suspected concussion. Remember, it is better to be safe.

Rest & Rehabilitation

After a concussion, the athlete should have physical rest and relative cognitive rest for a few days to allow their symptoms to improve. In most cases, after no more than a few days of rest, the athlete should gradually increase their daily activity level as long as their symptoms do not worsen. Once the athlete is able to complete their usual daily activities without concussion-related symptoms, the second step of the return to play/sport progression can be started. The athlete should not return to play/sport until their concussion-related symptoms have resolved and the athlete has successfully returned to full school/learning activities.

When returning to play/sport, the athlete should follow a stepwise, medically managed exercise progression, with increasing amounts of exercise. For example:

Graduated Return to Sport Strategy

Exercise step	Functional exercise at each step	Goal of each step
1. Symptom-limited activity	Daily activities that do not provoke symptoms.	Gradual reintroduction of work/school activities.
2. Light aerobic exercise	Walking or stationary cycling at slow to medium pace. No resistance training.	Increase heart rate.
3. Sport-specific exercise	Running or skating drills. No head impact activities.	Add movement.
4. Non-contact training drills	Harder training drills, e.g., passing drills. May start progressive resistance training.	Exercise, coordination, and increased thinking.
5. Full contact practice	Following medical clearance, participate in normal training activities.	Restore confidence and assess functional skills by coaching staff.
6. Return to play/sport	Normal game play.	

In this example, it would be typical to have 24 hours (or longer) for each step of the progression. If any symptoms worsen while exercising, the athlete should go back to the previous step. Resistance training should be added only in the later stages (Stage 3 or 4 at the earliest).

Written clearance should be provided by a healthcare professional before return to play/sport as directed by local laws and regulations.

Graduated Return to School Strategy

Concussion may affect the ability to learn at school. The athlete may need to miss a few days of school after a concussion. When going back to school, some athletes may need to go back gradually and may need to have some changes made to their schedule so that concussion symptoms do not get worse. If a particular activity makes symptoms worse, then the athlete should stop that activity and rest until symptoms get better. To make sure that the athlete can get back to school without problems, it is important that the healthcare provider, parents, caregivers and teachers talk to each other so that everyone knows what the plan is for the athlete to go back to school.

Note: If mental activity does not cause any symptoms, the athlete may be able to skip step 2 and return to school part-time before doing school activities at home first.

Mental Activity	Activity at each step	Goal of each step
1. Daily activities that do not give the athlete symptoms	Typical activities that the athlete does during the day as long as they do not increase symptoms (e.g. reading, texting, screen time). Start with 5-15 minutes at a time and gradually build up.	Gradual return to typical activities.
2. School activities	Homework, reading or other cognitive activities outside of the classroom.	Increase tolerance to cognitive work.
3. Return to school part-time	Gradual introduction of schoolwork. May need to start with a partial school day or with increased breaks during the day.	Increase academic activities.
4. Return to school full-time	Gradually progress school activities until a full day can be tolerated.	Return to full academic activities and catch up on missed work.

If the athlete continues to have symptoms with mental activity, some other accomodations that can help with return to school may include:

- Starting school later, only going for half days, or going only to certain classes
- More time to finish assignments/tests
- Quiet room to finish assignments/tests
- Not going to noisy areas like the cafeteria, assembly halls, sporting events, music class, shop class, etc.
- Taking lots of breaks during class, homework, tests
- No more than one exam/day
- Shorter assignments
- Repetition/memory cues
- Use of a student helper/tutor
- Reassurance from teachers that the child will be supported while getting better

The athlete should not go back to sports until they are back to school/learning, without symptoms getting significantly worse and no longer needing any changes to their schedule.

Davis GA, et al. Br J Sports Med 2017;0:1–8. doi:10.1136/bjsports-2017-097506SCAT5