Changes in cognitive function and cerebral oxygenation patterns in rugby and non-contact sportspersons over a 15-week season.

By

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ABSTRACT

Rugby is a contact team sport and is one of the most popular sports in South Africa and internationally. Recently, a growing body of research has highlighted that repeated concussive and subconcussive head contacts suffered during contact sport participation may have implications on athletes' health later in life. Of particular concern is the notion that the accumulation of these blows to the head may spark progressive neurodegeneration in the form of diseases such as chronic traumatic encephalopathy (CTE). Despite these concerns, the focus of research in rugby appears to be on the diagnosis and acute treatment of concussive injury, with little thought given to the long-term consequences.

The purpose of this study was to broaden our understanding of the effect of short-term exposure to physical contact on the brains of rugby players who participate in high-level contact sport competition. The primary aim of the study was to determine whether a fifteen-week season elicit a change in the cognitive function and cerebral oxygenation of rugby players when compared with age and sex matched non-contact athletes. The secondary aim was to determine whether changes in sleep quantity and quality, as well as mood states, took place that have the potential to impact the cognitive function and cerebral oxygenation of the participants.

Twenty-nine university athletes (16 rugby players (21,3 ± 1,35 yrs) and 13 non-contact sport athletes (20,8 ± 1,97 yrs)) were assessed before and after the 2017 Varsity Cup rugby competition (± 15 weeks). Each participant completed the CNS Vital Signs® Core testing battery, with measurements of cerebral oxyhaemoglobin ($\Delta[O_2Hb]$), deoxyhaemoglobin (Δ[HHb]), tissue oxygenation index (TOI) and normalised total haemoglobin index (nTHI) conducted simultaneously throughout testing. The cognitive testing battery consisted of seven tests that assessed eleven cognitive domains, giving an overall estimate of cognitive function. Additionally, participants' mood states and sleep status (quality and quantity) were measured prior to cognitive and cerebral oxygenation analysis each session.

Overall, cognitive function did not change for either group over the 15-week season (ES = 0,11 and 0,06 for Rugby and Control, respectively). Cerebral oxygenation measurements did not reflect any unexpected changes within the Control group, however, relative Δ[HHb] (ES = 0,57) and nTHI (P = 0,01; ES = 1,29) were significantly increased at post-testing in the rugby players. These variables are considered indirect indicators of oxygen consumption and cerebral blood flow rate, respectively.

Thus, while the rugby players' cognitive performance was maintained, alterations to cerebral oxygenation data took place that may be the result of participation in their sport. These findings may suggest that subtle impairments are beginning to take place within the brains of the players. Therefore, although a 15-week season may not have been enough to induce obvious negative changes in rugby players' cognitive function, exposure to contact over the course of multiple seasons may cause neural impairments to the extent that cognitive function, and health, are affected later in life. Despite these notions, it is recognised that changes in mood state and sleep pattern of the players may have confounded the results. Thus, additional research is required to further build on the sentiments proposed in this study.

Keywords: rugby, concussion, subconcussion, neuro-degeneration, encephalopathy

ABSTRAK

Rugby is ‘n kontak spansport en een van die mees populêre sportsoorte in Suid-Afrika en in die wêreld. Onlangse navorsing wys toenemend daarop dat herhaaldelike kontak teen die kop tydens deelname aan kontaksport, of dit konkussief of sub-konkussief is, mag implikasies inhou vir die gesondheid van atlete in hulle latere jare. Wat veral kommerwekkend is, is die aanspraak dat die voortdurende kontak teen die kop oor jare progressiewe neuro-degenerasie in die vorm van siektes soos kroniese traumatiese enkefalopatie (KTE) mag veroorsaak. Ongeag hierdie bekommernis, blyk dit dat die fokus van navorsing in rugby konsentreer op die diagnose en akute behandeling van harsingskudding en min aandag aan die langtermyn nagevolge.

The doel van hierdie studie was om ons begrip oor die effek van korttermyn blootstelling aan fisieke kontak op die breine van rugbyspelers wat aan ‘n hoë vlak kompetisie deelneem, te verbreed. Die primêre doelwit van die studie was om te bepaal of ‘n 15-weke seisoen ‘n verandering in die kognitiewe funksie en serebrale oksigenasie van rugbyspelers veroorsaak, in vergelyking met nie-kontak atlete van dieselfde ouderdom en geslag. Die sekondêre doelwit was om te bepaal of veranderinge in slaap kwantiteit en kwaliteit, asook gemoedstoestand plaasvind, wat die potensiaal het om die kognitiewe funksie en serebrale oksigenasie van deelnemers te beïnvloed.

Nege en twinting universiteitvlak atlete (16 rugbyspelers (21,3 ± 1,35 jr) en 13 nie-kontak sport atlete (20,8 ± 1,97 jr)) was voor en na die 2017 Varsitybeker kompetisie ondersoek (± 15 weke). Elke deelnemer het die CNS Vital Signs® Core toetsbattery afgelê, terwyl metings van serebrale oksihemoglobien ($\Delta[O_2Hb]$), deoksihemoglobien ($\Delta[HHb]$), weefesel oksigenasie-indeks (TOI) en genormaliseerde hemoglobienindeks (THI) op dieselfde tyd gemaak is. Die kognitiewe toetsbattery het uit sewe toetse bestaan waarmee elf kognitiewe domeine getoets is en waarna ‘n globale telling vir kognitiewe funksie bereken is. Deelnemers se gemoedstoestand en slaapstatus (kwaliteit en kwantiteit) is ook tydens elke sessie voor die kognitiewe en serebrale oksigenasie analise bepaal.

In die geheel was daar geen verandering in kognitiewe funksie oor die 15 weke seisoen in enige van die twee groepe nie (ES = 0,11 en 0,06 vir Rugby en Kontrole, respektiewelik). Daar was geen onverwagse veranderinge in die serebrale oksigenasie metings van die Kontrole groep nie, maar relatiewe $\Delta[HHb]$ (ES = 0,57) en nTHI (P = 0,01; ES = 1,29) het betekenisvol verhoog tydens die post-toetsing in die rugbyspelers. Hierdie veranderlikes word as indirekte merkers van onderskeidelik suurstofverbruik en serebrale bloedvloei beskou.

Hoewel die kognitiewe funksie van die rugbyspelers onveranderd gebly het, was daar veranderinge in die oksigenasie data wat moontlik toegeskryf kan word aan die deelname aan hulle sport. Hierdie resultate mag dui op die aanvang van subtiele veranderinge in die breine van die spelers. Hoewel die 15 weke seisoen dalk nie genoeg was om opvallende negatiewe veranderinge in die kognitiewe funksie van die rugbyspelers te veroorsaak nie, sal die blootstelling aan kontaksport oor verskeie seisoene neurale veranderinge veroorsaak wat kognitiewe funksie en gesondheid op die lange duur negatief sal beïnvloed. Dit moet egter in gedagte gehou word dat veranderinge in die gemoedstoestand en slaappatrone van die spelers wel die resultate kon beïnvloed het. Meer navorsing is dus nodig om voort te bou op die argumente in hierdie studie.

Sleutelwoorde: rugby, konkussie, subkonkussie, neuro-degenerasie, enkefalopatie

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LIST OF ABBREVIATIONS AND ACRONYMS

Δ	:	Delta (change of)
%	:	Percentage
<	:	Smaller than
>	:	Greater than
≤	:	Smaller than or equal to
≥	:	Greater than or equal to
$\Delta[O_2Hb]$	:	Change in concentration of oxyhaemoglobin
Δ[HHb]	:	Change in concentration of deoxyhaemoglobin
ACSM	:	American College of Sports Medicine
AD	:	Alzheimer's disease
ANOVA	:	Analysis of Variance
ATP	:	Adenosine triphosphate
CI	:	Confidence interval
Cm	:	Centimetre
CNS	:	Central nervous system
CO_2	:	Carbon dioxide
CPT	:	Continuous Performance Test
CSF	:	Cerebrospinal fluid
CTE	:	Chronic traumatic encephalopathy
CV_{co2}	:	Cerebral-vascular reactivity to CO_2
DLPFC	:	Dorsolateral prefrontal cortex
DMN	:	Default mode network
DTI	:	Diffusion Tensor Imaging
EAAs	:	Excitatory amino acids
EEG	:	Electroencephalogram
ES	:	Effect Size
F3	:	EEG position frontal 3
F4	:	EEG position frontal 4
F7	:	EEG position frontal 7
F8	:	EEG position frontal 8
fMRI	:	Functional Magnetic Resonance Imaging
fNIRS	:	Functional near-infrared spectroscopy

Fp1	:	EEG position prefrontal 1
Fp2	:	EEG position prefrontal 2
Fpz	:	EEG position mid-line prefrontal
FTT	:	Finger Tapping Test
Fz	:	EEG position mid-line frontal
GTs	:	Glial tangles
H	:	Hours
HHb	:	Deoxyhaemoglobin
HIT	:	Head Impact Telemetry
Hz	:	Hertz
K	:	Constant for light scattering
Kg	:	Kilogram
L	:	Large effect
LED	:	Light emitting diode
LPFC	:	Left prefrontal cortex
M	:	Moderate effect
Mean	:	Average
Mean diff.	:	Mean difference
Min	:	Minutes
mTBI	:	Mild traumatic brain injury
MTI	:	Magnetic Transfer Imaging
MTL	:	Medial temporal lobe
N	:	Number
N	:	No effect
NFL	:	National Football League
NFTs	:	Neurofibrillary tangles
NIR	:	Near-infrared light
NIRS	:	Near-infrared Spectroscopy
Nm	:	Nanometre
O_2Hb	:	Oxyhaemoglobin
Oz	:	EEG position mid-line occipital
P	:	Probability
PCS	:	Post-concussion syndrome
PET	:	Position Emission Topography
rCBF	:	Regional cerebral blood flow

S	:	Small effect
SAT	:	Shifting Attention Test
SDC	:	Symbol digit Coding
SIS	:	Second impact syndrome
$Sj0_2$	:	Jugular bulb oxygen saturation
SMA	:	Supplementary motor area
STEMS	:	Stellenbosch Mood Scale
Stroop 1	:	Stroop test part 1
Stroop 2	:	Stroop test part 2
Stroop 3	:	Stroop test part 3
SVC	:	Superior vena cava
SvO_2	:	Central venous oxygen saturation
THI	:	Normalised total haemoglobin index
TOI	:	Tissue oxygenation index
u20	:	Under 20 years of age
USA	:	United States of America
VBM	:	Verbal Memory Test
VIM	:	Visual Memory Test
VL	:	Very large effect
µM	:	Micromol
Yrs	:	Years

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CHAPTER ONE

INRODUCTION

A. Background

Rugby Union (from here on referred to as rugby) is a collision-based team sport played across a variety of age groups and skill levels ranging from primary school to professional. Concussions are a common occurrence in rugby with incidences being ranked among the highest in contact sports worldwide (Gardner *et al.*, 2014). Concussions are a form of mild traumatic brain injury caused by a blow to the body or head that transmits an impulsive force on the brain (McCrory *et al.*, 2013). A concussion results in a temporary impairment of neurological function accompanied by a variety of symptoms such as dizziness, nausea, headaches or loss of consciousness (Barkhoudarian *et al*., 2011; McCrory *et al.*, 2013). While the effects of a concussion may appear temporary, there has been a growing body of evidence that repeated concussions and blows below concussive thresholds, termed subconcussions, may have a chronic detrimental effect on the brains of contact sport participants (Shuttleworth-Edwards and Radloff, 2008; Bailey *et al.*, 2013; Kontos *et al.*, 2014; Talavage *et al.*, 2014; Abbas *et al.*, 2015). Of particular concern is the theory that the accumulation of repetitive blows to the head lead to progressive neurological decline in the form of diseases such as chronic traumatic encephalopathy (CTE).

CTE is a neurodegenerative disease characterised by a progressive decline in executive cognitive function, memory, depression and eventually dementia (Omalu *et al.*, 2005; Stern *et al.*, 2011; McKee *et al.*, 2015). Symptoms only present themselves years after retirement from sport and an official diagnosis can only be made post-mortem (Stern *et al.*, 2011; McKee *et al.*, 2015). The majority of cases have been reported in American football and boxing, however, there have also been a few incidences of CTE in retired amateur rugby players (Maroon *et al.*, 2015). The repeated blows to the head typically experienced in contact sport is thought to trigger a neurological cascade that leads to progressive neurodegeneration (Lucke-Wold *et al.*, 2014; McKee *et al.*, 2015). However, it is unknown whether onset of the disease can be caused by a single concussion or repeated minor events and if there are other risk factors such as genetics which bring about the disease (Stern *et al.*, 2011).

Recently, a number of studies have been conducted examining the effect that participation in various contact sports has on the brain. Most of these studies focused on sports such as American football, boxing and soccer, with participants ranging from high school athletes to the professional level and

retirement from professional play (Breedlove *et al.*, 2012; Koerte *et al.*, 2012; Bailey *et al.*, 2013; Ford *et al*., 2013; Kontos *et al.*, 2014; Talavage *et al.*, 2014; Slobounov *et al.*, 2017). Researchers observed changes in functional brain connectivity, impaired cerebral haemodynamic function and impaired neurocognitive function of contact sport participants (Breedlove *et al.*, 2012; Koerte *et al.*, 2012; Bailey *et al.*, 2013; Ford *et al*., 2013; Kontos *et al.*, 2014; Talavage *et al.*, 2014; Slobounov *et al.*, 2017). In a number of these studies changes in neurological function have been observed even in the absence of diagnosed concussions in the participants (Koerte *et al.*, 2012; Talavage *et al.*, 2014; Slobounov *et al.*, 2017). The authors hypothesised that these changes could be the result of repeated subconcussive blows and expressed their concern over what the cumulative effects of these blows would be over the course of multiple seasons of play.

In rugby the focus of research regarding head contact has been on concussion, its diagnosis, acute effects and treatment, with relatively little thought given to possible long-term effects of concussion and repetitive contact on the brain. Of the few studies that exist, changes have been found in the resting functional brain network of players after a single rugby match, as well as reductions in attentional skills over the course of a rugby season, and compromised visuomotor processing speed and cognitive function in both active and retired players (Shuttleworth-Edwards and Radloff, 2008; Shuttleworth-Edwards *et al*., 2008; Johnson *et al.*, 2014; Hume *et al.*, 2017). To the author's knowledge no studies thus far have examined the effect of contact on the neurophysiology of rugby players over the course of a season or competition.

Despite the growing body of evidence on the potential long-term consequences of head contact in rugby, players' and coaches' knowledge of concussion and head contact remains limited. Studies reported poor awareness of the limitations of supposed safety equipment, return to play guidelines, and the potential consequences of concussion and returning to play before being medically cleared (Baker *et al.*, 2013; Walker, 2015; O'Connell and Molloy, 2016). Medical staff have also reported pressure to clear a concussed player as being very common (Fraas *et al.*, 2015). This displays a clear need for research that can be used to educate players and coaches on the potential consequences of contact on the brain. This is especially relevant as the game continues to develop, with players becoming bigger, faster, and stronger, and continually increasing season lengths, even at school level (Coughlan *et al.*, 2011; Hartwig *et al*., 2011). Players and parents have a right to know if there are any potential unseen consequences to their neurological function as the result of them, or their children, stepping onto the field of play.

B. Motivation

There is increasing evidence that head trauma that falls both above and below the threshold required to induce concussive brain injury may have chronic negative effects on neurocognitive function. Pathologists have found indicators of neurodegenerative brain diseases such as CTE in athletes who have never been clinically diagnosed with a concussion but participated in contact sports (Gavett *et al*., 2011; Baugh *et al.*, 2012). Additionally, impairments to the neurological and cognitive function of contact sport participants have been observed in multiple studies (Breedlove *et al.*, 2012; Koerte *et al.*, 2012; Bailey *et al.*, 2013; Ford *et al.*, 2013; Kontos *et al.*, 2014; Talavage *et al.*, 2014; Slobounov *et al.*, 2017). Thus, the typical contact suffered by athletes in contact sports may be more damaging than previously thought. Rugby is a sport with a high frequency of collisions, thus players may be exposed to high levels of accumulated head contacts over the course of a match, season or years of play and this may have detrimental effects on players' cognitive function later in life (King *et al.*, 2014). Changes in the functional connectivity of the brain have been demonstrated in rugby players after a single match and cognitive function in retired players has previously been found to be impaired (Johnson *et al.*, 2014; Hume *et al.*, 2017). However, function of the brain during cortical activation in rugby players is yet to be explored. With an ever-increasing emphasis being placed on player safety there is a need for research that examines the effects that a season or competition has on players' brains and cognitive function so that players and parents may understand the potential unseen consequences, or lack thereof, that come with stepping onto the rugby pitch.

C. Purpose

There is a paucity of evidence suggesting that participation in rugby may have long-term consequences on the global cognition and brain function of players. The purpose of this study was to broaden our understanding of the effect of short-term exposure to physical contact on the global cognitive function and cerebral oxygenation of players who participate in a high-level contact sport competition.

D. Research Questions

1. Primary Research Question: Does a fifteen-week season elicit a change in the cognitive function and cerebral oxygenation of rugby players when compared with age and sex matched non-contact athletes?

It is hypothesized that cerebral oxygenation responses will be reduced in the rugby players at the post-testing period, and that this reduced response will be accompanied by decreased cognitive performance. These responses would be due to the accumulation of microtraumas throughout the brain as the result of the repetitive head contact suffered by the players throughout the season. This is based on the findings of similar studies that have observed impaired cerebral haemodynamics and cognitive function in contact sport athletes compared with non-contact controls (Shuttleworth-Edwards and Radloff, 2008; Damian M Bailey *et al.*, 2013; Talavage *et al.*, 2014; Hume *et al.*, 2017). It is hypothesized that these changes will not be evident in non-contact sport athletes because they have not suffered the equivalent amount of head contact as the rugby players.

2. Secondary Research Question: Are there changes in sleep quantity and quality, as well as mood states in rugby players which may impact their cognitive function and cerebral oxygenation?

It is hypothesized that changes that may be observed in sleep patterns and mood states at the end of the competitive season will not have an effect on cognitive function and cerebral oxygenation, neither in rugby players, nor non-contact sport athletes. Previous evidence showed that, typically, only severe alterations in mood state and sleep influence cognitive function and cerebral oxygenation (Walker and Stickgold, 2004; Butts *et al.*, 2013; Esposito *et al.*, 2015; Kreutzmann *et al.*, 2015; Shields *et* al., 2016).

E. Research Objectives

Primary Objectives:

1. Determine the global cognitive function and corresponding cerebral oxygenation of the rugby players prior to, and upon completion of the 2017 Varsity Cup rugby competition.
2. Determine the global cognitive function and corresponding cerebral oxygenation of the non-contact athletes prior to, and upon completion of a fifteen-week participation period.
3. Determine whether changes to the global cognitive function and cerebral oxygenation of the participants took place over the course of the study and if these changes are associated with the contact suffered during sporting participation.

Secondary Objectives:

1. Determine the anthropometric measurements of the participants.
2. Determine mood state and sleep status of the participants prior to the pre- and post-testing assessments of the participants.
3. Monitor the amount of practice and playing time of the participants over the course of the study.
4. Determine whether any alterations to mood state or sleep status had an effect on the global cognitive function and cerebral oxygenation of the participants.

CHAPTER TWO

CONCUSSION AND HEAD TRAUMA IN SPORT

A. Introduction

Concussion is a form of mild traumatic brain injury (mTBI) that affects millions of people worldwide each year, particularly participants in contact sports such as rugby union, American football and boxing (McCrory *et al.*, 2013; Williams *et al.*, 2015; Hay *et al.*, 2016). Recently, the potential long-term effects of concussion and repetitive head trauma in contact sport, such as chronic traumatic encephalopathy (CTE), have come under attention in the public and academic sector due to case studies conducted on several high profile sportsmen (Omalu *et al.*, 2005, 2006; Stern *et al.*, 2011; McKee *et al.*, 2015). A basic understanding of the science of concussion is required in order to further explore the consequences of contact sport participation on the brain.

B. Defining Concussion and Subconcussion

1. Concussion

Sports related concussion (hereafter referred to as concussion), is defined by authors of an International Consensus Statement at the 5th International Conference on Concussion in Sport, as a form of brain injury brought about by biomechanical forces suffered during sporting participation that induce a complex pathophysiological process affecting the brain (McCrory *et al.*, 2017). Concussions may be caused by a blow to the head or body that transmits an impulsive force on the brain, resulting in short lived neurological function impairment that resolves spontaneously (McCrory *et al.*, 2013). Concussion may or may not involve loss of consciousness and may include one or more of the following symptoms: headache, confusion, gait abnormalities, amnesia, personality change (irritability, depressive thoughts, laziness, etc.) nausea and sleep disturbances (Barkhoudarian *et al.*, 2011; McCrory *et al.*, 2017). Symptoms typically resolve spontaneously, however, they may evolve and progress within the first minutes to hours following injury (McCrory *et al.*, 2017). Traditionally, acute concussion was thought to be the result of a functional disturbance rather than a structural injury as typically no structural changes may be observed with standard structural neuroimaging scans. However, in certain patients symptoms may have a more lasting effect which develop into conditions such as post-concussion syndrome (Patricios *et al.*, 2010; Barkhoudarian *et al.*, 2011; McCrory *et al.*,

2017). Despite the existence of a formal definition (McCrory *et al*., 2017), there is still ongoing debate as to the most effective diagnostic criteria for concussion as a definitive diagnostic tool is yet to be developed. Thus, it is speculated by researchers and medical practitioners that many concussions go undiagnosed within the sporting arena (Meehan *et al.*, 2013; O'Connell and Molloy, 2016).

2. Subconcussion

Lately, there has been more interest into contact incidents in sport, frequently termed "subconcussions", in the literature. A subconcussion is a blow or impulsive force to the head that does not fulfil all the criteria to diagnose a clinical concussion (King *et al.*, 2014; Belanger *et al*., 2015). Apart from possible direct head contact during a collision, rapid acceleration-deceleration forces are placed on both the body and the brain when an athlete experiences a contact event (Smith *et al.*, 2012; Turner *et al.*, 2012). The brain sits within a fluid medium in the cranial cavity with relatively free movement, thus making it susceptible to injury via these acceleration-deceleration forces in what is known as the slosh effect (Smith *et al.*, 2012; Turner *et al.*, 2012). Some authors consider subconcussion to be a theoretical construct due to the debate over what level of force constitutes a subconcussion and how a subconcussive blow differs from any regular non-clinical blow to the head or lower threshold concussions (Belanger *et al.*, 2015). Despite these uncertainties, there is still growing concern that the burden of repetitive subconcussive forces on the brain may result in the accumulation of microtraumas that eventually lead to disrupted neurofunction or degenerative neuropathology later in life (Gavett *et al.*, 2011; Baugh *et al.*, 2012).

C. Basic Pathophysiology of Concussion

A concussion is caused by biomechanical forces acting on the brain. These forces induce a complex pathophysiological process in the form of a neurometabolic cascade that impacts neurological function (Barkhoudarian *et al.*, 2011; Signoretti *et al.*, 2011). A basic understanding of this cascade is required to better understand the potential consequences that come with concussion and head impact in sport.

1. The Neurometabolic Cascade of Concussion

Immediately after mechanical insult, neuronal cell membrane disruption and axonal stretching occurs (Barkhoudarian *et al.*, 2011). This causes a massive flux of ions through the cell membranes which in turn results in the release of neurotransmitters and excitatory amino acids (EAAs), in particular, glutamate (Barkhoudarian *et al.*, 2011; Signoretti *et al.*, 2011; Giza and Hovda, 2015). This leads to

further ionic flux and the ATP-dependant sodium/potassium ion pumps within the cell membranes are forced to work at full capacity in order to re-establish homeostasis. What results is hyperglycolysis as the cells try to generate sufficient ATP for the ion pumps leading to a depletion of cellular energy stores. This, combined with reduced cerebral blood flow, leads to an uncoupling between energy supply and demand in the cells (Barkhoudarian *et al.*, 2011; Giza and Hovda, 2015). Significant calcium influx occurs into the cells, which is taken up by intracellular mitochondria and results in oxidative stress. This does not only further impact the cellular energy crisis, but it also produces damaging free radicals that may cause microtraumas within the cells (Giza and Hovda, 2015). After the initial injury the adverse sequalae spontaneously resolve and normal cellular functioning returns, however, glucose metabolism in the brain may go into an impaired state for up to 7-10 days, as shown in various animal models (Signoretti *et al.*, 2011).

D. Potential Consequences of Concussion and Head Contact

While the symptoms and neurological disturbances associated with concussion are typically transient and spontaneously resolve within several days, there are incidences where symptoms continue to persist in athletes and hamper activities of daily living. Added to this are several potential short and long-term consequences to concussion, repeated concussions and repetitive head contact found in contact sport.

1. Post-Concussion Vulnerability

The period of metabolic impairment seen within the brain post-concussion is associated with increased cell vulnerability (Signoretti *et al.*, 2011; Giza and Hovda, 2015). This means that if a second impact is sustained while function is still being restored, a second concussion is likely to occur even if the level of force is well below that of a typical vector seen with concussion (Patricios *et al.*, 2010). If a second concussion does occur within this period it is generally more severe than the first concussion with more adverse symptoms that take longer to resolve and may even result in long term or permanent impairment of cognitive function (Giza and Hovda, 2015). Thus, it is of great importance that a contact sports person does not return to play within this time period, however, we are still unable to determine when this period of brain vulnerability resolves completely in athletes (Signoretti *et al.*, 2011; Giza and Hovda, 2015). It is also unknown whether a similar period of vulnerability exists in the brain after sustaining regular subconcussive contact in sport and whether sustaining multiple subconcussive knocks has a comparable cumulative effect on the brain.

2. Second-Impact Syndrome

There has been a handful of reported cases of catastrophic cerebral oedema following a repeated concussive episode that results in death of the patient (Barkhoudarian *et al.*, 2011; Signoretti *et al.*, 2011). This extremely rare phenomenon has been termed Second-Impact Syndrome (SIS) and is highly debated throughout literature due to its impact on return-to-play guidelines following a concussion, despite evidence of its existence being predominantly anecdotal and in the form of few reported case studies (McCrory and Berkovic, 1998; McCrory *et al.*, 2012).

SIS is thought to be caused by sustaining a second concussive impact while the brain is still recovering from a previous concussion (Dessy *et al.*, 2014). The initial concussion results in a period of impaired metabolic function and may cause increased cerebral blood volume post-injury which may lead to mild cerebral swelling. A second impact during this recovery period may cause complete failure of the brain's cerebral vascular autoregulatory mechanisms (brain blood-flow control), resulting in massive cerebral oedema which brings about brainstem herniation and death (McCrory *et al.*, 2012). Further research is needed to determine whether SIS does in fact exist, the risk factors associated with its occurrence, and how it can be prevented.

3. Post-Concussion Syndrome

In the majority of patients post-concussion symptoms resolve within a few days to weeks, however, in a large number of cases symptoms continue to persist for months or even years in what is known as post-concussion syndrome (PCS) (Ryan and Warden, 2003; Messé *et al.*, 2013; Ellis *et al.*, 2016). PCS may appear in a combination of physical, cognitive, and psychological/emotional symptoms such as persistent recurring headaches, dizziness, noise and light sensitivity, fatigue, sleep disturbances, memory and learning problems, depression, anxiety and irritability (Ryan and Warden, 2003; Chong, 2008; Ellis *et al.*, 2016). Some researchers believe that PCS may result from subtle structural disturbances inflicted by the initial injury which challenges the traditional view that concussion is merely a temporary functional disturbance (Messé *et al.*, 2013; Ellis *et al.*, 2016). This is worrying as it suggests that concussion and head contact has a more lasting and damaging effect than has been previously thought.

4. Chronic Traumatic Encephalopathy

Recently significant attention has been placed on the potential long-term effects of repetitive head trauma in contact sport which manifests as a disease known as chronic traumatic encephalopathy (CTE). Originally identified in professional boxers and known as "punch-drunk" or *dementia pugilistica*, CTE involves chronic pathological neurodegeneration with progressive symptomology eventually resulting in death (McKee *et al.*, 2013, 2015; Hay *et al.*, 2016). While appearing similar to Alzheimer's Disease (AD) and other neurodegenerative disorders, CTE is a distinct disease and typically presents itself years after the individual has retired from competitive play (Omalu *et al.*, 2005; Stern *et al.*, 2011; McKee *et al.*, 2013).

4.1. Diagnosis

Official diagnosis of CTE can only be made post-mortem with extensive histopathological analysis of the brain tissue. Gross macroscopic changes to the tissue are only visible during very late stages of the disease and present as general atrophy of the brain accompanied by reduced brain weight (Gavett *et al.*, 2011; McKee *et al.*, 2015). More pronounced atrophy is typically found in the frontal and temporal cortices, as well as the thalamus, hypothalamus and mammillary bodies (McKee *et al.*, 2015). On a microscopic level CTE is characterised by coagulations of neurotoxic proteins, predominantly hyper-phosphorylated tau protein in the form of neurofibrillary tangles (NFTs), neurites, and glial tangles (GTs) (Omalu *et al.*, 2006; Baugh *et al.*, 2012; McKee *et al.*, 2015). The same type of protein coagulations also exists in AD, however, the distribution of these proteins in CTE follows a distinct pattern different to that of other neurodegenerative disorders (Omalu *et al.*, 2005; Gavett *et al.*, 2011; McKee *et al.*, 2015). The fact that CTE can currently only be diagnosed post-mortem poses a critical issue into the management and prevention of the disease. Presently, clinicians have to rely on symptomology that grossly overlaps with various other conditions and diseases such as PCS and AD (Faden and Loane, 2015). Thus, there is a need for research into the development of techniques for the recognition and diagnosis of CTE *in vivo*.

4.2. Symptoms

The symptoms of CTE generally only appear in middle age; years, or even decades, after the individual ceased participation in the sport or symptoms from any acute head trauma have stopped. By this time the level of neurodegeneration is great enough to cause clinically recognisable disturbances (Gavett *et al.*, 2011; Stern *et al.*, 2011; McKee *et al.*, 2013). Symptoms are commonly classified as cognitive, mood and behavioural and the progressive nature of the disease means that symptoms worsen as time progresses (McKee *et al.*, 2015). Early symptoms are typically behavioural or cognitive. In some reports patients are often described by family members and friends as becoming

irritable and quick to anger with a "short fuse", while others report difficulties with learning and memory (Gavett *et al.*, 2011). Other early symptoms include: cognitive; problems with executive function (planning, organisation, judgement, etc.), behavioural; substance abuse, increased aggression/violence, disinhibition, mood; depression, apathy and suicidality (Gavett *et al*., 2011; McKee *et al.*, 2015). As the disease progresses it begins to affect motor function, such as difficulty with balance and gait, as well as speech changes (slurring of words, slower speech, etc) (McKee *et al.*, 2015). In a few cases patients have developed dementia, however, it is uncommon as usually morbidity occurs before the disease is able to reach this state (Baugh *et al.*, 2012).

4.3. Prevalence

The prevalence of CTE is difficult to determine due to a confirmed diagnosis only being possible post-mortem, as well as the absence of large scale randomised studies on the brains of contact sport athletes (Gavett *et al.*, 2011). Our knowledge on CTE and its prevalence comes from collections of case studies on athletes whose families donated their brains to researchers when it was suspected that the athlete may have had CTE. Thus, there is a large amount of selection bias in the reported prevalence of CTE in contact sport, with researchers unable to produce a reliable estimate of its occurrence (McKee *et al.*, 2013; Tator, 2014; Maroon *et al.*, 2015; Hay *et al.*, 2016). To date, most of the confirmed CTE cases have been professional boxers and American footballers. CTE has also been found in other contact sport athletes such as ice hockey and rugby, as well as soccer players, military personnel exposed to blast trauma and victims of prolonged physical abuse (McKee *et al.*, 2013; Maroon *et al.*, 2015). It should be noted that there are also many incidents of deceased contact sport athletes without any evidence of CTE (Hazrati *et al.*, 2013). Large scale randomised studies conducted outside of the USA are needed to determine a realistic prevalence of CTE in the international athletic population so that we may better understand the risks involved with participating in a contact sport.

4.4. Causes and Risk Factors

It is thought that the onset of CTE is caused by head trauma that may be concussive or subconcussive. Repetitive head trauma is theorised to set off an irreversible neurometabolic cascade as seen in a concussion, however, this cascade leads to the development of tau protein coagulations and progressive neurodegeneration (Lucke-Wold *et al.*, 2014). Despite this theory, it has not yet been conclusively determined that repetitive head trauma is the cause of CTE, however, there exists a strong association between a history of repetitive head contact and development of the disease (McKee *et al.*, 2015; Hay *et al.*, 2016).

There have also been studies that have associated the amount of contact exposure over the course of an athlete's career with the severity of symptoms and level of neurodegeneration upon histological examination (Bailey *et al.*, 2013; McKee *et al.*, 2013). This infers that repetitive head trauma may be considered a risk factor for the development of CTE. However, it is still unknown whether the onset of CTE may be caused by just a single concussive impact or the cumulative effect of repeated smaller contacts, as cases exist where patients had no history of clinically diagnosed concussion but have had years of exposure to subconcussive contacts (Omalu *et al.*, 2005; McKee *et al.*, 2013). It is also unknown to what degree factors such as sex, age upon contact exposure and genetics play in the potential risk of developing the disease (Gavett *et al.*, 2011; Hay *et al.*, 2016). Determining what role these factors play and how physical contact affects the brain is crucial in developing management systems for athletes and preventing the occurrence of CTE.

E. Head Contact and Concussion in Rugby

Rugby Union (rugby) is a contact team sport of an intermittent nature with periods of high intensity activity interspersed with periods of low intensity activity and is played at a variety of levels ranging from primary school to professional (Coughlan *et al.*, 2011). A large portion of the game revolves around contact situations, thus concussions and subconcussive head trauma are common throughout the game. In South Africa, rugby is one of the country's most popular sports with over 460 000 participants of whom a large number are school children (World Rugby, 2016). This potentially implies that a large number of young people may be suffering regular repetitive mild head trauma. An understanding of how common incidents of head trauma are in rugby and how they affect players is crucial to player safety and development of the game, as it continues to grow locally and internationally.

1. The Incidence of Head Trauma in Rugby

There have been a number of studies on the incidence of concussion in rugby. An international meta-analysis of available rugby concussion data up to 2014 found a mean concussion incidence of 4,73 per 1000 match playing hours (Gardner *et al.*, 2014). This is relatively high when compared to other contact sports such as American football (0,48 – 4,56/1000 playing hours), ice hockey (1,55/1000 playing hours) and soccer (0,49/1000 playing hours) (Benson *et al.*, 1999; Gessel *et al.*, 2007; Clay *et al.*, 2013). The review also found that incidence rates varied across levels of play and that match play incidence was much greater than training (0,07 concussions per 1000 playing hours) (Gardner *et al.*, 2014). A more recent study on the incidence of concussion in youth rugby (age groups under 13 to under 18) in South Africa found a higher rate of concussions, with 6,8 per 1000 match hours

(Mc Fie *et al.*, 2016). Studies have also examined how the use of protective gear, such as scrumcaps, affects concussion. It was found that they do not prevent concussion but may reduce the risk of other injuries, such as scalp lacerations (McIntosh *et al.*, 2009; Navarro, 2011).

There is a shortage of studies on the number of subconcussive impacts that occur during rugby matches and training. A study conducted on high level club rugby players in New Zealand, using mouthgaurd accelerometers, reported that participants sustained a mean of 95 ± 133 subconcussive impacts per player per match (King *et al.*, 2014). The researchers used a minimal threshold of 10 *g* linear acceleration to define subconcussive hits, as non-contact activities such as running, jumping and walking have been shown to produce peak linear accelerations up to that level (King *et al.*, 2014).

2. Player Knowledge

Multiple studies have examined the level of concussion knowledge that rugby players, coaches and management staff possess. Knowledge of concussion is important within the sport as it affects the recognition of concussion symptoms during matches, as well as more effective management of concussed athletes, such as adherence to return to play protocols. A study on sub-elite South African rugby players found that participants had less than optimal knowledge of concussions and that knowledge on return to play protocols and safety equipment was particularly bad (Walker, 2015). Alarmingly, 74% of players stated a willingness to participate in practice before being cleared by a medical professional, while 47-56% stated they would participate in a match before being cleared to play (Walker, 2015). Similar findings have been reported in studies conducted in Ireland on senior and u20 players of varying levels of competition (Baker *et al.*, 2013; O'Connell and Molloy, 2016). Nevertheless, Fraas *et al*. (2015) reported that team management, more so than coaches, generally possessed accurate knowledge of concussion and management of concussed players.

Summary

Repeated brain trauma in the form of concussive and subconcussive blows is extremely common in contact sports, particularly rugby. Apart from the initial acute sequalae of symptoms following concussion there are other potential consequences of repetitive contact that may have serious negative long-term effects on the brain. Despite the seriousness of concussion and its potential consequences, player knowledge on the condition and correct return to play protocols is reportedly poor. There is a need for research into the effects of repetitive head contact on the brain so that we may better understand the potential consequences of participating in contact sport and thus improve player safety and management.

CHAPTER THREE

THE BRAIN, COGNITIVE FUNCTION AND CONTACT SPORT

A. Introduction

Recent media attention has sparked interest into the possible effects of cumulative head-trauma suffered by contact sport athletes (Stern *et al.*, 2011; Baugh *et al.*, 2012). It is thought that repetitive microtrauma suffered by the brain during contact sport play may lead to cognitive dysfunction or neurodegenerative disorders later in life (McKee *et al.*, 2015). The brain is the most complex organ in the body and thus the relationship between contact sport and neurofunction is not simple. Researchers have conducted studies to analyse the direct effects of contact sport on the brain by investigating the cognitive function of contact sport athletes, as well as their brain structure and functional activation.

B. The Brain

1. Basic Function and Anatomy

The brain is a critical component of the central nervous system (CNS) which controls thought and, along with the endocrine system, regulates bodily function (Sherwood, 2012). The brain is comprised of soft nervous tissue that is vulnerable to damage and is unable to regenerate, thus its protection is vital. The brain is encased in several layers namely the cranium (skull), three meninges (nourishing membranes) and cerebrospinal fluid which flows in the space between the ventricles (Yoshitani *et al.*, 2007; Sherwood, 2012). These layers serve to protect the brain from direct trauma, absorb shock, and supply blood and nutrients (Sherwood, 2012).

The brain itself is divided into three major areas; the brain stem, the cerebellum and the forebrain (consisting of the diencephalon and cerebrum) (Abler *et al.*, 2006; Petersen and Posner, 2012; Sherwood, 2012 ; Diamond, 2013). Each of these areas are further divided into smaller, more specialised regions responsible for certain functions. However, no region of the brain operates in isolation from the rest of the brain, thus multiple regions are constantly active, interpreting, co-ordinating and executing various functions (Miller and Wallis, 2009; Petersen and Posner, 2012; Wong *et al.*, 2015).

The brain stem is directly attached to the spinal cord and consists of the medulla, pons, and midbrain. It is responsible for basic functions required to sustain life, such as digestion, respiration and circulation (Sherwood, 2012). The cerebellum is attached to the top-rear section of the brain stem and is responsible for maintaining bodily position in space, and for coordinating conscious and subconscious movement (Abler *et al.*, 2006; Witt *et al.*, 2009; Wong *et al.*, 2015).

The diencephalon is located on top of the brainstem in the interior of the cerebrum and consists of the hypothalamus and thalamus (Sherwood, 2012). These regions play a significant role in the endocrine system and homeostasis, as well as some primitive sensory functions. The cerebrum makes up the largest portion of the brain and consists of an outer layer of grey matter, the cerebral cortex and a thick central core of white matter that contains basal nuclei (Sherwood, 2012). The cerebral cortex is involved in more complex neural functions, such as voluntary movement initiation, sensory perception and interpretation, language, personality traits and higher cognitive functions such as thinking, self-awareness, memory and learning (Frith and Dolan, 1996; Poldrack and Gabrieli, 1998; Alvarez and Emory, 2006; Jansen *et al.*, 2009; Kim *et al.*, 2011; Petersen and Posner, 2012).

The functions and structure of the cerebrum are of greater relevance to the current study and thus will be discussed in further detail below.

2. The Cerebrum

The cerebrum is divided into two hemispheres, left and right, by a thick band of tissue, termed the corpus callosum (Poldrack and Gabrieli, 1998; Jansen *et al.*, 2009; Sherwood, 2012). Each hemisphere consists of four major lobes, namely the occipital, temporal, parietal and frontal lobes (Sherwood, 2012). Different neural functions can be attributed to certain areas on each lobe, thus if a certain area of the cerebral cortex is damaged we can expect to see deviations in the functions related to that area of the brain.

2.1. The Occipital and Temporal Lobes

The occipital lobes are located on the posterior portion of the cerebrum. They are involved in the initial processing of visual information received via the optic nerve (Sherwood, 2012). The temporal lobes are located on the lateral portions of each hemisphere and primarily deals with initial interpretation of auditory information (Sherwood, 2012). The temporal lobe also contains the Limbic Association Cortex which plays a role in emotion and feelings of motivation, as well as memory (Jansen *et al.*, 2009; Wixted and Squire, 2011).

2.2. The Parietal Lobes

The parietal lobes are located on the top rear portion of the cerebrum. The primary role of the parietal lobes is receiving and processing sensory information such as touch, pain, pressure and heat (Sherwood, 2012). This information is received and processed in the somatosensory cortex, a band running down the length of the parietal lobe. The somatosensory cortex is also involved in proprioception and awareness of the body in space (Sherwood, 2012).

2.3. The Frontal Lobes

The frontal lobes are located on the front upper portion of the cerebral hemispheres (Sherwood, 2012). They are involved in complex functions, such as voluntary motor action, speech, and the process of conscious thought (Alvarez and Emory, 2006; Kim *et al.*, 2011; Diamond, 2013). The primary motor cortex is located on the rear portion of the frontal lobes and deals with voluntary control of skeletal muscle contractions that result in movement (Sherwood, 2012; Wong *et al.*, 2015). The parietal-temporal-occipital association cortex of the frontal lobe integrates all sensory information received from other parts of the brain and enables us to interpret and understand the body's relation to the external environment (Sherwood, 2012).

The prefrontal cortex is located on the front portion of the frontal lobe. It is the region responsible for conscious thought and cognitive functions such as planning, decision making, creativity, working memory and personality traits (Alvarez and Emory, 2006; Diamond, 2013).

The prefrontal cortex is the area most relevant to the current study as many of the functions mentioned above have previously been shown to be affected by repetitive head contact.

C. Contact Sport and Cognitive Function

1. Cognitive Function

Cognitive functions are brain processes that are involved in acquiring and understanding knowledge and interpreting our surrounding environments (Diamond, 2013). Cognitive functions can be divided into higher and lower order functions (Frith and Dolan, 1996; Miller and Wallis, 2009). Lower order functions are involved in basic information retrieval and retention, while higher level, or executive functions, are involved in integrating and coordinating processes into thought and actions, directing them at achieving certain goals (Smith *et al.*, 1996; Miller and Wallis, 2009; Diamond, 2013). Examples of lower order cognitive functions are memory, attention, fine motor control and basic sensory input and interpretation. These are processes that are generally thought to be routine, without

requiring excessive conscious effort, however, they are still more complex and require more conscious effort than basic autonomic functions required to maintain homeostasis (eg. breathing) (Frith and Dolan, 1996; Diamond, 2013). Executive functions encompass processes such as thought, planning, inhibition, cognitive flexibility, learning and working memory (Miller and Wallis, 2009). Executive functions are extremely complex and makes simultaneous use of the majority of lower order cognitive functions to achieve the desired outcomes (Miller and Wallis, 2009; Diamond, 2013).

Commonly researched cognitive functions and their corresponding brain regions are explained in more detail below.

2. Core Cognitive Domains and Associated Brain Regions

2.1. Memory

Memory is the process of encoding, storing and retrieving acquired knowledge either consciously or subconsciously for later recall (Gabrieli, 1998; Hwang and Golby, 2006; Sherwood, 2012). There are two stages of memory storage, namely short-term memory and long-term memory (Sherwood, 2012). Short-term memory can only be retained for up to a few hours before it needs to be consolidated into long-term memory which can be retained for days to years (Gabrieli, 1998; Jansen *et al.*, 2009). Two of the most commonly researched memory domains are verbal and visual memory. Verbal memory refers to the memory of words and language while visual memory involves aspects of visual information, such as the recall of objects, images, people, animals and locations (Jansen *et al.*, 2009; Shang and Gau, 2011).

The brain does not contain a specific memory centre; instead, multiple regions are involved in the retention and retrieval of information. The cortical regions predominantly involved in memory are the medial temporal lobe (MTL) and hippocampus (Gabrieli, 1998; Slotnick, 2004; Jansen *et al.*, 2009). Verbal and visual memory tend to be processed on opposing hemispheres, with visual memory encoding located in the right MTL and verbal memory in the left MTL (Hwang and Golby, 2006; Jansen *et al.*, 2009).

2.2. Attention

Attention is the cognitive process of selectively concentrating on a discrete stimulus or set of stimuli while simultaneously disregarding other stimuli deemed irrelevant or harmful to the current task (Boersma and Das, 2008; Hilti *et al.*, 2013). Attention is required for multiple cognitive functions as it allows us to focus on a task without being distracted, however, the attention system does not involve the actual processing of information and decision making (Petersen and Posner, 2012). Two

commonly tested aspects of attention are simple and complex attention. Simple attention is the ability to concentrate on a single stimulus for a prolonged period of time, while complex attention requires tracking multiple sets of stimuli, or shifting sets of stimuli for lengthy periods (Hilti *et al.*, 2013; CNS Vital Signs®, 2017).

Several brain regions are involved in attentional processes. Basic arousal is based in the brain stem, while simple sustained attention and vigilance is right hemisphere dominant utilizing the superior parietal cortex and prefrontal cortex (Pardo *et al.*, 1991; Petersen and Posner, 2012; Hilti *et al.*, 2013). Complex attention tasks require larger degrees of executive control and inhibition and thus use more frontal midline brain regions, such as the medial frontal cortex and anterior cingulate (the region surrounding the front of the corpus callosum) (Posner and Rothbart, 1998; Petersen and Posner, 2012).

2.3. Motor Speed and Psychomotor Speed

Motor speed can be defined as the ability to perform simple fine motor tasks quickly and accurately to achieve a set objective (CNS Vital Signs®, 2017). Psychomotor speed links motor speed with more complex cognitive tasks and may be defined as the ability to perform simple motor tasks in response to complex visuo-perceptual information (CNS Vital Signs®, 2017).

Motor speed uses cortical regions such as the supplementary motor area (SMA) and primary sensory motor cortex, as well as the cerebellum and basal ganglia in the white matter (Abler *et al.*, 2006; Witt *et al*., 2009; Wong *et al.*, 2015). Psychomotor speed requires a number of executive processes such as inhibition, rules adherence, complex information processing and decision-making. Thus, in addition to areas used for motor control and speed, the execution of fine motor tasks employs extensive activation of the prefrontal cortex (Wong *et al.*,2015; Hwang *et al.*, 2016).

2.4. Executive Functions

Executive functions are considered cognitive processes that coordinate thoughts and information to produce action directed at achieving set goals (Miller and Wallis, 2009; Diamond, 2013). Core executive functions are the basis for higher level thoughts such as consciousness, self-regulation, reasoning and problem solving (Alvarez and Emory, 2006; Miller and Wallis, 2009). Core executive processes often tested to assess cognitive deficits are inhibition, working memory, planning and cognitive flexibility (Alvarez and Emory, 2006; Leber *et al.*, 2008; Miller and Wallis, 2009).

Inhibition is used to control our thoughts, actions and emotions by overriding internal predispositions or external stimuli and focusing on what is required in the moment (Miller and Wallis, 2009; Diamond, 2013). Inhibition is vital to other executive processes such as complex attention and self-

discipline, where success is reliant on not responding to distractors and completing the task at hand (Diamond, 2013).

Working memory is the process of retaining information within the mind and mentally manipulating and working with it (Carpenter *et al.*, 2000; Diamond, 2013). It acts as a short-term memory buffer for holding information that can be related to later problems. Working memory, however, is distinctly different from short term memory as short term memory does not involve the manipulation of information or its application to related situations (Diamond, 2013). Working memory is used in all forms of problem solving such as mental arithmetic and is vital to everyday function (Carpenter *et al.*, 2000; Alvarez and Emory, 2006).

Cognitive flexibility may be defined as the ability to respond to rapidly changing stimuli or situations, or to be able to quickly change one's opinions or tactics regarding a specific task (Leber *et al.*, 2008; Diamond, 2013; CNS Vital Signs®, 2017). Cognitive flexibility makes use of both inhibitory control and working memory (Diamond, 2013). It is used in tests where instructions are liable to change or to overcome problems by changing the approach when other options are not working (Leber *et al.*, 2008).

Executive functioning occurs predominantly in the prefrontal cortex of the frontal lobe, particularly the dorsolateral prefrontal cortex (Frith and Dolan, 1996; Carpenter *et al.*, 2000; Alvarez and Emory, 2006; Diamond, 2013). However, because executive functions make use of a number of lower cognitive functions, multiple other regions, such as the medial temporal lobe and posterior parietal cortex, are recruited during various executive function tests (Carpenter *et* al., 2000; Alvarez and Emory, 2006).

3. Factors Affecting Cognitive Function

Apart from age and disease, there are several factors that may affect an individual's cognitive function. This includes, sleep, stress, physical exercise, fitness levels, caffeine intake and alcohol consumption. The effects of sleep on cognitive function have been well documented and it has been found that sleep deprivation or impairments in sleep quality have a negative influence on cognitive function, particularly learning and memory (Walker and Stickgold, 2004; Esposito *et al.*, 2015; Kreutzmann *et al.*, 2015; Kang *et al.*, 2016).

It is also well known that both acute and chronic psychological stress impacts an individuals' emotional and cognitive health (McEwen and Sapolsky, 1995; Mendl, 1999). While it is generally accepted that chronic stress negatively impacts cognitive function, acute bouts of stress may have an

enhancing effect on aspects of cognitive function (Mendl, 1999; Shields *et al*., 2016). A person in a stressful situation may experience a narrowing of attention, enhancement of memory, or increased decision-making speed (Mendl, 1999). However, this appears dependant on the amount of stress and the arousal state of the individual. When the stressors become too severe cognitive performance diminishes (Mendl, 1999; Butts *et al*., 2013; Shields *et al*., 2016).

The relationship between exercise and cognitive function has been previously examined. Studies have found that both acute exercise bouts and physically active life styles are associated with higher cognitive performances (Chang *et al*., 2015; Vestberg *et al.*, 2012; Gomez-Pinilla and Hillman, 2013; Jacobson and Matthaeus, 2014). Acute bouts of moderate intensity exercise lasting 20 min has been shown to improve executive function in young healthy men (Chang *et al.*, 2015). Individuals who are more physically active and aerobically fit have been shown to perform better in various cognitive function assessments. This effect also continues with age, namely reducing the rate of age related cognitive decline (Vestberg *et al.*, 2012; Gomez-Pinilla and Hillman, 2013; Jacobson and Matthaeus, 2014). The benefits of exercise on cognitive function have been shown to be stronger for elite level sports persons. For example, elite soccer players had higher levels of executive function when compared to amateur players and non-sports persons (Vestberg *et al.*, 2012).

Caffeine and alcohol consumption in relation to cognitive function have also been studied. Acute alcohol intoxication has been shown to impair executive function as well as memory ability (Weissenborn and Duka, 2003; Poltavski *et al.*, 2011). Interestingly, sub-intoxication doses of alcohol have been shown to have minimal effects on the cognitive function of young men, and a low-dose (40 $mg.dl^{-1}$) may even have a facilitation effect on psychomotor speed (Hoffman and Nixon, 2015). Caffeine consumption is well regarded as having a stimulatory effect on cognitive function. It has been demonstrated that caffeine consumption, regardless of the mode of delivery, may improve cognitive function and alertness for up to 5 hours (Camfield *et al.*, 2014; Paulus *et al.*, 2015).

The above-mentioned factors must all be taken into account when examining cognitive function in healthy populations and should be controlled for where possible.

4. Current Literature on Contact Sport and Cognitive Function

It is generally accepted throughout literature and in clinical settings that sport related concussions cause temporary impairments in cognitive function (McCrory *et al.*, 2013). However, traditionally concussion was perceived as an acute medical issue with little thought given to the long term cumulative effects of concussions and subconcussions on athletes' cognitive function (Shuttleworth-Edwards and Radloff, 2008; Thornton *et al.*, 2008). In recent years, interest on the longer-term effects

has grown and researchers have examined the effects of participation in contact sports such as American football, boxing, rugby and soccer on the cognitive function of participants.

4.1 American Football

Researchers have analysed the cognitive function of American football players in relation to a number of different variables such as number of seasons participated, head contacts over the course of a season, effect of starting age of contact participation and the effect of a professional career (Ford *et al*., 2013; Casson *et al.*, 2014; Talavage *et al.*, 2014; Stamm *et al.*, 2015). A common tool for cognitive function measurement used by researchers in American football is the ImPACT™ testing battery designed for concussion detection (Nauman *et al.*, 2015). ImPACT™ measures six aspects of cognitive function, namely, verbal memory, spatial/visual memory, visual working memory, visual-motor speed, verbal working memory and cognitive speed (Nauman *et al.*, 2015).

Several studies have used ImPACT™ to assess the cognitive function of high school American football players at multiple time points over the course of a season (Breedlove *et al.*, 2014; Talavage *et al.*, 2014; Nauman *et al.*, 2015). A common finding in these studies was that cognitive function, particularly working memory, was frequently impaired throughout the season in players without a diagnosed concussion and that these impairments could generally be related to the number of head impacts sustained during the season (Breedlove *et al.*, 2014; Talavage *et al.*, 2014; Nauman *et al.*, 2015). Self-reported executive function has been described in active college and professional football players and it has been found that footballers experience more frequent executive function issues within daily life than healthy controls (Seichepine *et al.*, 2013).

Cognitive function has also been assessed in retired professional National Football League (NFL) players and it was found that larger portions of retired players exhibit cognitive dysfunction relative to healthy, non-contact sport, age-matched populations (Hart *et al.*, 2013; Casson *et al.*, 2014). A study by Ford *et al*. (2013) on the effect of concussion history on episodic memory of retired players with and without a history of concussion found that the number of concussions experienced by players during their careers had no effect on cognitive function. However, both player groups, with or without a history of concussion, exhibited memory impairments when compared to healthy non-sport controls (Ford *et al*., 2013).

An intriguing study by Stamm *et al*. (2015) looked into the effects of starting age of contact football exposure on cognitive function in retired professional NFL athletes using a variety of measures. Players who started American football participation before the age of 12 performed worse on all measures of cognitive function compared to players who started playing the sport at a later age

(Stamm *et al.*, 2015). This suggests that exposure to head contact from a young age influences cognitive outcome later in life in contact sport athletes.

4.2. Boxing, Soccer and Other Team Sports

Professional boxing careers have been associated with cognitive dysfunction and Parkinsonism later in life since as early as the 1920s (Martland, 1928). However, evidence supporting these deductions was largely anecdotal and based on the general appraisal of the behaviour of professional boxers (Martland, 1928; Butler *et al.*, 1993; Jordan, 2009). Recently, several studies have examined the effects of acute and long-term boxing participation on the cognitive function of participants.

An early study compared the cognitive function of amateur boxers to other contact sport athletes (rugby and water polo) (Butler *et al.*, 1993). All participants were measured pre-competition, post-competition and at a follow up session that occurred within two years. It was found that boxers performed worse than the controls on baseline measures of cognitive function, however, there was no difference between groups at any of the follow up measurements and no effect of sport participation on cognitive function within any group (Butler *et al.*, 1993).

A more recent study on the effects of a sparring session in amateur male and female boxers found that delayed memory trials were significantly impaired from pre-sparring assessments and that there were no gender related differences in results (Stojsih *et al.*, 2010). An earlier study on the cognitive function of male college boxers over the course of a seven day tournament found no change in cognitive function during the tournament and no difference in cognitive function when compared to age matched university controls (Moriarity *et al.*, 2004). Bailey *et al.* (2013) examined cognitive function in professional boxers and compared them to age-matched, fitness-matched, non-contact sport controls. The boxers underperformed on all the measures of cognitive function which included memory, attention, visuo-motor coordination and executive function.

Soccer and other team sports such as ice-hockey and lacrosse have previously been investigated regarding its effects on players' cognitive function. While soccer players experience fewer concussions compared to other contact sports, they experience large numbers of subconcussive impacts due to frequent heading of the ball (Rodrigues *et al.*, 2016; Moore *et al.*, 2017). A study on the acute effects of soccer ball heading in female high school players found that participants experienced reduced inhibitory control after a standardised heading practice session when compared to non-soccer playing female students who did not perform any heading (Zhang *et al.*, 2013). Research in active amateur and university soccer players has found acute impairments in memory related to heading when compared to noncontact controls (Lipton *et al.*, 2013; Di Virgilio *et al.*, 2016; Moore *et al.*, 2017). However, a study by Stephens *et al.* (2010) involving high school soccer players

found no differences in player cognitive function when compared to age-matched controls of differing sports. Another study found higher levels of inhibitory control and cognitive flexibility in elite youth soccer players when compared to age-matched sub-elite youth soccer players even when differences in training time where taken into account (Huijgen *et al.*, 2015).The authors proposed that higher functioning of these domains was necessary for elite level soccer performance due to the requirements of players to quickly appraise and react to multiple and differing stimuli. The authors also suggested that quality of soccer training may also impact these cognitive domains by acting as a training stimulus (Huijgen *et al.*, 2015). The effect of soccer participation on cognitive function appears to differ throughout literature and further research is needed to better understand this relationship, however, participation in higher levels of soccer may result in improvement of certain executive functions when compared to lower levels of play.

Killam *et al*. (2005) compared the cognitive function of field hockey, ice hockey, lacrosse and soccer athletes with or without a history of concussion to non-athlete sport controls. The authors reported impaired memory function in all the sport groups, both with and without a history of concussion, compared to the non-athlete controls. However, there were no observed differences between any of the groups in Stroop task performance, a common measure of reaction time and executive function (Killam *et al.*, 2005).

4.3. Rugby

Compared to other contact sports, there have been fewer studies examining the effects of rugby participation on cognitive function. Two studies have been conducted in South Africa examining various facets of cognitive function in rugby players ranging from school level to the senior national team (Shuttleworth-Edwards *et al.*, 2008; Shuttleworth-Edwards and Radloff, 2008). Shuttleworth-Edwards and Radloff (2008) found that visuomotor processing speed was reduced in high-level rugby players of various age-groups when compared to age and playing level matched non-contact sport controls.

Shuttleworth-Edwards *et al*. (2008) examined the effect of a full rugby season (seven months) on the cognitive function of university rugby players in comparison to cricket and hockey players. It was found that only attention was reduced in the rugby players compared to the controls at the post-season measurement and that this difference was due to an increase in the control athletes' scores while the rugby players' scores remained the same (Shuttleworth-Edwards *et al.*, 2008). Another study that year examined the effect of concussion history in rugby players and found that retired amateur players with a history of concussion exhibited more clinical post-concussion symptoms compared to active

players with or without a history of concussion (Thornton *et al.*, 2008). However, none of the groups differed on scores of neurocognitive function (Thornton *et al.*, 2008).

A more recent study on retired international Scottish rugby players found that participants had reduced verbal memory and learning scores and impaired fine-motor coordination compared to none-contact controls (McMillan *et al.*, 2017). Recently, Hume *et al*. (2017) conducted a large-scale study on retired elite and community rugby players and compared the effects of concussion history and participation in the sport on cognitive function with age matched retired non-contact sport controls. The study used an extensive computerized neurocognitive testing battery and it was found that retired elite rugby players performed worse on tests of complex attention, processing speed, executive functioning and cognitive flexibility compared to non-contact athletes, and worse in complex attention compared to retired community players (Hume *et al.*, 2017). The retired community players also performed worse on measures of executive function and cognitive flexibility compared to non-contact athletes (Hume *et al.*, 2017). Additionally, players with a history of concussion from all groups performed worse than players without a history of concussion in the domains of cognitive flexibility, executive function and complex attention.

D. Contact Sport and Neurophysiology

1. Neuroimaging techniques

A number of instruments and methods can be used to observe and analyse brain activity while at rest or completing tasks. Some of the most common methods used in research on contact sports are Diffusion Tensor Imaging (DTI), Magnetic Transfer Imaging (MTI), Functional Magnetic Resonance Imaging (fMRI), Position Emission Topography (PET) and Near-Infrared Spectroscopy (NIRS) (Belanger *et al.*, 2007). Neuroimaging techniques are generally classified as structural or functional. Structural techniques such as DTI and MTI detect changes in structural brain composition due to injury or atrophy (Belanger *et al.*, 2007; Jones and Leemans, 2011). Functional techniques such as fMRI, PET and NIRS are used to observe brain activity and activation at rest or during tasks and allow us to see which areas of the brain are used for certain functions, and to what degree they are activated to achieve a certain task (Phelps, 2000; Belanger *et al.*, 2007; Lee *et al.*, 2013). Both fMRI and PET provide high resolution, real time, accurate, spatial analysis of the brain, however, they are both extremely costly, are not portable, and are not suitable for persons with extreme claustrophobia or sensitivity to noise.

NIRS was used in the current study and thus will be discussed in further detail below.

2. Near-Infrared Spectroscopy (NIRS)

2.1. Basic Principles of NIRS

NIRS is a non-invasive method for analysing regional blood oxygen saturation and haemoglobin content *in vivo* (Jöbsis, 1977; Madsen and Secher, 1999; Rolfe, 2000; Ferrari and Quaresima, 2012). NIRS is based on the principle that near-infrared light (NIL) of wavelengths between 700-1000 nm easily penetrates biological tissue (Jöbsis, 1977; Ferrari *et al.*, 2004; Ehlis *et al.*, 2014). NIL is fired into the tissue via a light emitting diode (LED) probe placed on the skin, is reflected along a banana shaped arch and is picked up by a receiving probe that is usually placed between 2-5 cm away (Strangman *et al.*, 2003; Ferrari *et al.*, 2004). As the NIL passes through tissue it is attenuated either via absorption by chromophores found within biological compounds, or via complex light scattering within the diverse layers of tissue (Madsen and Secher, 1999; Rolfe, 2000; Ferrari *et al.*, 2004; Ferrari and Quaresima, 2012).

The peak absorption spectra of oxyhaemoglobin (O_2Hb) and deoxyhaemoglobin (HHb) is known to be approximately 850 nm and 760 nm, respectively (Madsen and Secher, 1999). Thus, using a modified Beer-Lambert Law, the approximate changes in O_2Hb and HHb concentrations may be calculated (Rolfe, 2000; Ferrari *et al.*, 2004; Lee *et al.*, 2013). This enables the calculation of oxygen saturation, also known as tissue oxygen index (TOI), within the tissue as well as normalised total haemoglobin index (nTHI = $k$$O_2Hb$ + kHHb, where k is the constant for light scattering), which is related to blood volume (Ferrari and Quaresima, 2012; Green *et al.*, 2016). It has previously been shown that with an increase in brain activity there is an associated increase in cerebral blood flow without a concurrent increase in cerebral oxygen consumption, demonstrated by an increase in O_2Hb and decrease in HHb within the region (Villringer and Chance, 1997; Gratton *et al.*, 2001). This pattern of increased cerebral haemodynamic activity with cortical activation is controlled by a process known as neurovascular coupling. The exact mechanisms of neurovascular coupling are currently under debate. However, it is thought that increased cortical activation leads to an increase in a number of factors such as vasoactive ions (K^+ and H^+), cerebral metabolism and resulting metabolites, and neurotransmitters (Girouard *et al.*, 2014). These changes result in vasodilation of the surrounding arterioles leading to an increase in cerebral blood flow and O_2Hb concentration. Thus, measurement of the changes in O_2Hb and HHb concentrations within the brain via NIRS is regarded a good measure of cortical activation of the region under investigation (Schroeter *et al.*, 2002).

2.2. Typical Oxygenation Patterns During Cognitive Tasks

Performing cognitive tasks causes an increase in brain activity and this results in an increase in cerebral blood flow to the activated regions of the brain (Villringer and Chance, 1997; Madsen and

Secher, 1999; Ehlis *et al.*, 2014). This is typically demonstrated by a proportional increase in O_2Hb and normalised total haemoglobin index (nTHI), and a decrease in HHb (Villringer and Chance, 1997; Gratton *et al.*, 2001; Ehlis *et al.*, 2014). Current literature on NIRS agrees with these findings and the expected O_2Hb and HHb patterns have been demonstrated in tasks involving memory, attention, motor control and executive function (Schroeter *et al.*, 2002, 2004; Franceschini *et al.*, 2003; Toichi *et al.*, 2004; Sakatani *et al.*, 2006; Matsui *et al.*, 2007; León-Carrion *et al.*, 2008; Ferreri *et al.*, 2014). Interestingly, the degree of O_2Hb increase has been shown to be greater in voluntary motor tasks than involuntary tasks, and greater in incongruent *versus* congruent Stroop tasks (Schroeter *et al.*, 2002; Franceschini *et al.*, 2003). Previous studies have also shown that higher levels of activation (elevated O_2Hb) are associated with better performances in modified Stroop tasks, as well as increased activation in memory tasks involving both word encoding and recall, as opposed to recall only tasks (Matsui *et al.*, 2007; León-Carrion *et al.*, 2008). These findings infer that with increasing task complexity comes higher levels of cortical activation, thus a greater change in O_2Hb and HHb concentrations within the tissue, and that improved performance on certain cognitive tasks may be associated with greater increases in cortical activation.

While the pattern of O_2Hb increase during cortical activation is consistent throughout literature there exists some debate over the pattern of HHb changes during cognitive tasks (Ferreri *et al.*, 2014). Several studies have shown that HHb levels may in fact not decrease, but either increase slightly or remain the same during cortical activation (Meek *et al.*, 1995; Toichi *et al.*, 2004; Ehlis *et al.*, 2005; Ferreri *et al.*, 2014). An increase in HHb may indicate a greater rate of oxygen utilization within that region of the brain (Toichi *et al.*, 2004). However, researchers are not yet certain as to why these differing patterns in HHb concentration occur.

2.3. Factors Affecting Cerebral NIRS Measurement

2.3.1. Skull Thickness and Cerebrospinal Fluid (CSF) Area

The depth of NIL penetration within the tissue is a function of the distance between the emitting and receiving probes, with peak depth being approximately half the distance between the probes (Strangman *et al.*, 2003; Ferrari *et al.*, 2004). The recommended distance between probe placement used on the adult skull is 4-5 cm, thus the peak depth of NIL penetration is approximately 2-2,5 cm (Madsen and Secher, 1999; Ferrari *et al.*, 2004). Cranial thickness and cerebrospinal fluid area vary greatly in the adult population with skull thicknesses ranging between 0,4 cm to 2 cm and CSF area generally occupying between 0,25-0,52 cm^2. Thus NIRS measurements on individuals with thicker skulls and greater CSF areas may be affected, as has been demonstrated previously in literature (Dehghani and Delpy, 2000; Okada and Delpy, 2003; Yoshitani *et al.*, 2007).

2.3.2. Skin Blood Flow/ Temperature

It has been hypothesised that an increase in skin blood flow during NIRS measurement, due to increased skin temperature, may affect the quality of readings (Madsen and Secher, 1999; Davis, 2006; Ferreri *et al.*, 2014). This is a conflicting topic in literature with some studies reporting no effect of skin blood flow when controlled for via tourniquet (Fantini *et al.*, 1996). However, other researchers have demonstrated that a localised or whole body increase in temperature results in significantly greater levels of O_2Hb measurement (Davis, 2006).

2.3.4. Alternate Factors

There are a number of factors that may have an effect on cerebral NIRS measurements over the prefrontal cortex that can typically be resolved with correct application and placement of the NIRS measurement probes. These include skin pigmentation, external light exposure, the position of the frontal sinus in the skull and position of the temporalis muscle (Madsen and Secher, 1999; Strangman *et al.*, 2003; Ferrari *et al.*, 2004; Minati *et al.*, 2011). It has been previously shown that darker skin pigmentations may result in NIRS signal loss due to the absorption of light by melanin (Wassenaar and Van den Brand, 2005). Thus, the reliability of NIRS measurements on individuals with darker skin pigmentation will be reduced. External light from the sun and other sources may affect readings and thus must be controlled for by appropriate covering of the measurement probes with dark cloth or material (Ferrari *et al.*, 2004).

The frontal sinus is a hollow space located just superior of the bridge of the nose and may affect NIRS measurements if the emitting probe is placed over it, thus it must be taken into account when applying the probes to the skin (Ferrari *et al.*, 2004; Okada *et al.*, 2010; Ferreri *et al.*, 2014). The position of the temporalis muscle on the lateral aspect of the forehead must also be taken into account when applying measurement probes as oxygenation of this muscle will affect measurements of the cerebral tissue (Madsen and Secher, 1999; Ferrari *et al.*, 2004; Ferrari and Quaresima, 2012).

2.4. Validity of NIRS

Previous studies demonstrated that NIRS measurements are generally validated and consistent with other modalities of cerebral oxygenation measurement (Nagdyman *et al.*, 2004, 2005; Lee *et al.*, 2008; Lynch *et al.*, 2014). Nagdyman *et al*. (2004) examined the relationship between cerebral tissue oxygen index and central venous oxygen saturation (SvO_2) in children who had undergone corrective heart surgeries. The simultaneous measurements of TOI and SvO_2 showed a strong correlation of $r = 0{,}52$ ($P < 0{,}001$) (Nagdyman *et al.*, 2004). Nagdyman *et al*. (2005) also compared cerebral TOI to jugular bulb oxygen saturation (SjO_2) and reported a strong correlation ($r = 0{,}81$ $P < 0{,}001$) between the measures.

Lynch *et al*. (2014) compared NIRS measurements to oxygen saturation levels of blood samples from the super vena cava (SVC), the clinical gold standard for cerebral oxygenation, in both paediatric patients and healthy adult participants. There was a strong correlation between measures in the paediatric participants (R^2 = 0,81; P = 0,001), and cerebral oxygen saturation in the adult participants was at a level expected by the researchers (79,4 ± 6,8%) (Lynch *et al.*, 2014). Previous research has also found strong correlations between NIRS and fMRI measurements during identical cognitive tasks (Lee *et al.*, 2008).

3. Neurophysiological Changes in Contact Sport Participants

There have been numerous studies in the literature examining how contact sport participation affects the brain. The majority of studies have been conducted on American football players, largely due to increased media coverage involving retired American footballers and CTE (Baugh *et al.*, 2012; Raftery, 2014). Other contact sports such as boxing, basketball, soccer, and rugby have also been examined. The most common technique used to assess brain structure has been fMRI, however, researchers have also assessed cortical activation with NIRS and other imaging modalities such as DTI and PET (Belanger *et al.*, 2007).

3.1. NIRS Studies

Few studies have used NIRS on contact sport athletes, as the concept of using NIRS to detect functional changes in brain physiology is still relatively new. Bailey *et al*. (2013) assessed neurocognitive and cerebral haemodynamic function in professional boxers using NIRS and a number of other techniques such as transcranial doppler. The study found that cerebral haemodynamics was chronically impaired in all of the boxers and that impairments in cerebral-vascular reactivity to CO_2 (CV_{co2}) was correlated to poor performance in the neurocognitive tests (Bailey *et al.*, 2013). Kontos *et al*. (2014), using functional NIRS (fNIRS) on recently concussed (15 - 45 days) sportspersons, found smaller changes in O_2Hb in response to tasks assessing memory, attention and executive function when compared to healthy controls. Oxygenation measurements were taken over the frontal and temporal regions of the brain and researchers hypothesized that the changes were due to either impaired neurovascular coupling, impaired metabolic function, or direct damage to the vascular network of the brain.

These findings are supported by a recent study on functional brain oxygenation of sportspersons exhibiting chronic post-concussion symptoms (Helmich *et al.*, 2015). Individuals who exhibited severe post-concussion symptoms were found to have decreased brain oxygenation in the frontal regions of the brain during a working memory task when compared to healthy controls with no history of concussion. Interestingly, this trend was also seen within the left dorsolateral prefrontal cortex

(DLPFC) when compared to previously concussed individuals exhibiting mild to no post-concussive symptoms. Furthermore, oxygenation levels were negatively correlated with severity of symptoms (Helmich *et al.*, 2015).

3.2. Other Neuroimaging Studies

In recent years studies have been conducted that have extensively analysed the brains of American football players with the use of imaging modalities such as fMRI and PET scanning. Researchers have investigated what effect playing American football has on functional brain connectivity, cortical activation, brain metabolism, brain structure and cerebral blood flow in both acute and longitudinal terms (Ford *et al.*, 2013; Talavage *et al.*, 2014; Abbas *et al.*, 2015; Poole *et al.*, 2015; Myer *et al.*, 2016). Populations examined have ranged from high school athletes through college and to the professional level. Some studies have found reduced levels of cortical activation, cerebrovascular reactivity, metabolism and impaired white matter integrity in accordance with NIRS studies mentioned earlier (Talavage *et al.*, 2014; Poole *et al.*, 2015; Shenk *et al.*, 2015; Svaldi *et al.*, 2015; Myer *et al.*, 2016). However, other studies have found changes in functional connectivity patterns during cognitive tasks and even increased levels of cerebral activation during resting and working mental states (Breedlove *et al.*, 2012, 2014; Ford *et al.*, 2013; Abbas *et al.*, 2015; Slobounov *et al.*, 2017).

Abbas *et al.* (2015) attempted to provide an explanation for the functional hyperconnectivity demonstrated in their study. They proposed that the brain responds to a subconcussive blow in a similar, but reduced, manner as a concussion. The mechanical loading of the blow alters neurophysiological function and may overcome the compensatory mechanisms of the brain and over prolonged periods of exposure this could lead to axonal tract impairment (Abbas *et al.*, 2015). This forces the brain to make use of parallel pathways to maintain function and over time (eg. a sporting season) enough of these pathways are activated to produce the observed hyperconnectivity (Abbas *et al.*, 2015). Interestingly, despite discovering differing cerebral activation patterns, authors have commonly reported that detected changes in neurophysiology are related to the amount of blows a player sustains over the course of their study (Breedlove *et al.*, 2012, 2014; Talavage *et al.*, 2014).

Sports such as soccer, rugby, rugby league, boxing and other combat sports have also been examined. Studies on soccer and combat sports have found abnormalities in white matter microstructure, reduced brain volume, increased cortical thinning, thinning of the corpus callosum and reduced levels of glucose metabolism in the brains of participants (Handratta *et al.*, 2010; Provenzano *et al.*, 2010; Koerte *et al.*, 2012, 2016; Gajawelli *et al.*, 2013; Lipton *et al.*, 2013; Simmons *et al.*, 2013).

There are far fewer studies on rugby, however, researchers in rugby league have found evidence of reduced levels of glutathione in retired professional players, indicating potential neurotrauma or neurodegeneration (Gardner *et al.*, 2017). Johnson *et al*. (2014) conducted a fMRI study on the acute effects of a rugby match on the default mode network (DMN), a resting state brain network, of college rugby players. Players were split into two groups, namely those with a history of past concussion *versus* no history of concussion, and players were tested before and after a single match. It was found that players with a history of concussion had significantly reduced brain activation levels during the pre-match measurement compared to players without a history of concussion (Johnson *et al.*, 2014). Furthermore, it was found that a single match had an effect on the DMN of both player groups. Those with a history of concussion tended to exhibit decreased levels of DMN activation post-match, while players without a concussion history tended to exhibit hyperactivity of the DMN (Johnson *et al.*, 2014). This suggests that a history of prior concussions has an impact on how the brain reacts to further incidences of contact.

Summary

Numerous studies analysing a variety of contact sports have found evidence suggesting that repetitive head contacts may have both acute and lasting effects on brain structure and function. However, there is also conflicting evidence that contact-sport participation may have a negligible effect on the brain or in some instances may even enhance cognitive function, at least in the short term. This may be due to the complex attentional strategies required by team sport players, or perhaps the cognitive benefits associated with aerobic exercise. In the context of rugby, relatively few studies have been conducted analysing the effects of cumulative head contact on the brains of players. Further research into these effects is needed to broaden our understanding of contact sport and the brain.

CHAPTER FOUR

METHODS

A. Study Design

A cross-sectional analytic observational study design was employed consisting of an observational Rugby group and a non-contact sport Control group. Each participant attended a single study briefing session and two testing sessions. Rugby participants underwent pre-testing prior to the commencement of the 2017 Varsity Cup Rugby tournament in January and post-testing after the tournament completion in April. The Control group underwent pre-testing from February through to early April during regular class scheduling and post-testing from May to the end of June.

Participation in the 2017 Varsity Cup Rugby competition, as well as the training sessions conducted by the team served as the exposure for the rugby players. Training and sport participation of the Control group was monitored during the study with the use of personal training diaries (Appendix E). Pre-testing consisted of the completion of a personal details form (Appendix B), a health questionnaire (Appendix C), a mood state questionnaire (Appendix D) and a body composition analysis, as well as assessment of the participants' cognitive function and cerebral oxygenation. Post-testing involved only the cognitive function and cerebral oxygenation testing as well as the mood state questionnaire.

B. Participants

1. Participant Selection

Participants in the Rugby group were male university rugby players recruited from the Stellenbosch University 2017 Varsity Cup Rugby squad. The Control group consisted of age and sex matched non-contact sportsmen recruited from various sport clubs within the university. These clubs included the university's hockey and squash club, as well as students of the Department of Sport Science. Participants were recruited during team meetings prior to their training sessions. Thirty-nine (39) participants (24 rugby players and 15 non-contact sport athletes) aged between 18 and 25 years volunteered to participate in the study. All the participants were informed of the purpose and procedures of the study and gave their full, written consent (Appendix A) to participate. Additionally, participants were informed of the criteria for participation in the study (e.g. history of

neuropsychiatric disorder, concussive injury or use of chronic medication) so that they understood their own eligibility for participation.

2. Inclusion and Exclusion Criteria

Participants were included if they were male, aged between 18 and 25 years and were enrolled as students at Stellenbosch University. Rugby players were required to be a member of the 2017 Stellenbosch University Varsity Cup squad. Control athletes were required to participate in a non-contact sport that included regular training each week (minimum of three sessions per week). Participants from both groups were required to be university degree students from Stellenbosch University. Exclusion criteria included a diagnosis of concussion in the two months prior to the start of the study, a history of neuropsychiatric disorder or addiction and the current use of chronic medication. Participants were also excluded from the study if they suffered an injury that resulted in more than two consecutive weeks out from training or match play, if they were diagnosed with a concussion during the course of the study, if they did not complete all testing procedures, either out of choice or due to illness/injury, or if they did not follow the preparation guidelines prior to testing (section C.2.).

3. Assumptions

It was assumed that all participants performed to the best of their abilities throughout all testing procedures and were honest in answering all questionnaires pertaining to health, sleep status, mood state, alcohol consumption and medication use. It was assumed that all participants were honest in reporting symptoms of concussion or injury during the period of the study that may have resulted in exclusion from the study.

4. Delimitations

The Rugby group was limited to players who were part of the Stellenbosch University Varsity Cup squad. The Control group was limited to male Stellenbosch university non-contact sport athletes, in order to control for age and sex. Both groups were limited to currently enrolled Stellenbosch University degree students. Data analysis did not include any participants who suffered a diagnosed concussion over the course of the study. Cognitive testing assessed the domains given by the CNS Vital Signs Core testing protocol and cerebral oxygenation measurements were limited to the left prefrontal cortex.

C. Experimental Design

1. Information Session

The information session for the Rugby group took place during a team meeting prior to a training session. The information sessions for the Control athletes were conducted either at team training or individually at the Stellenbosch University Department of Sport Science. The session consisted of an overview of the study and testing procedures. The procedure for the neurocognitive testing battery, as well as the NIRS analysis, were explained and was followed by an opportunity for the participants to ask questions about aspects of the study or tests that they were unsure of. Finally, participants were given consent forms (Appendix A) that they were requested to read before signing.

2. Laboratory Visits

A summary of the testing sessions can be seen in Figure 4.1. Testing took place at the University of Stellenbosch Sport Science Department. All testing was conducted by the researcher. Body composition analysis and relevant pen and paper questionnaires were completed in the department's Sport Physiology laboratory. Cognitive function and cerebral oxygenation testing were conducted in a quiet, secluded room with minimal distractions for the participant. Each testing session lasted between 50 minutes to 1 hour and 20 minutes.

The participants were required to obtain at least 6 hours of sleep and to refrain from alcohol and caffeine intake for 24 and 12 hours, respectively, before each testing session. If any of these conditions were not met, the session was rescheduled for the next day or a later date. Upon arrival at the venue, participants sat in a comfortable chair facing the desk in the Sport Physiology laboratory. The session began with the participant filling in the personal details form (Appendix B) and Stellenbosch Mood Scale (STEMS) questionnaire (Appendix D), followed by measurement of the participant's body composition. The Control group additionally completed a health screening questionnaire (Appendix C) prior to testing. Health clearance for the rugby players was obtained from the team doctor prior to testing. The Control group participants were also instructed how to complete the training diary over the course of the study (Appendix E). Training participation of the Rugby group was monitored in person by the researcher at the players' training sessions and match participation was monitored via video analysis by the researcher. Additionally, players that were frequently interchanged with the 2nd team were given a separate training diary (Appendix F) for sessions not conducted with the 1st team.

The participant and researcher then moved to the private room for cognitive testing and cerebral oxygenation measurement. Participants were seated in a comfortable chair facing a desk with a laptop. The NIRO-200NX Oxiometer was placed behind the participants on a separate desk, as to minimise possible distractions. Skull measurements were taken and the probes of the NIRO-200NX Oxiometer were applied to the forehead of the participant (see under D. Measurements). This was followed by baseline measurements of the participant's cerebral oxygenation. Each participant was required to sit still for a period of five minutes with their eyes closed and were asked to empty their mind and think as little as possible. While this was happening, cerebral oxygenation was monitored continuously with NIRS. Upon completion of the baseline measurements, the participant began the CNS Vital Signs Core testing battery on the laptop. Cognitive testing lasted approximately 30 min per person and cerebral oxygenation was monitored continuously throughout testing. When cognitive testing was completed the participant was asked to remain seated with their eyes closed for five more minutes, while recovery cerebral oxygenation data was measured.

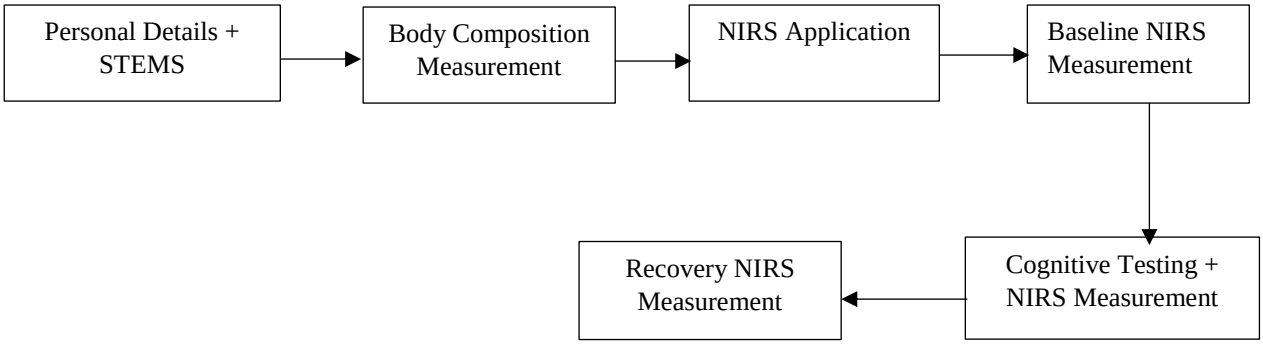


Figure 4.1. Experimental procedure.

3. Ethical Aspects

The study protocol was approved by the Research Ethics Committee for Humanities of Stellenbosch University (Reference number SU-HSD-003916). Further permission was also acquired from the relevant management teams, coaches and the team doctor for the 2017 Varsity Cup Rugby squad. Participation was completely voluntary and informed consent was obtained from all participants. They were able to withdraw from the study at any stage, without reason and without any consequences. Participation in the study and the resulting data collected had no impact on team selection of any players and the participants were reassured of this.

The researcher acted professionally and showed respect to the participants throughout the study. The study did not involve any invasive procedures and none of the testing procedures posed any risk to the participants' health or their ability to participate in their relevant sport. The participants were not discriminated against on the basis of race, social status, sexual orientation or academic performance. The participants' identity was not reported in any of the results and all individual data remains confidential. The coaches were also informed that if a participant was found to have abnormal cognitive functioning, indicating a deficit or serious injury, that they would be informed upon which they could decide their preferred method in notifying the player.

D. Measures and Tests

The primary outcome variables included the cognitive domain scores accompanying the CNS Vital Signs Core testing battery and changes in relative oxyhaemoglobin concentration ($\Delta[O_2Hb]$), deoxyhaemoglobin concentration (Δ[HHb]), tissue oxygenation index (TOI) and normalised total haemoglobin index (nTHI). Secondary outcome variables included anthropometric measurements and body composition, as well as training data, sleep data and mood state scores of the participants.

1. Anthropometric data

The participants' stature and body mass were recorded before pre-testing. Stature is defined as the perpendicular distance between the transverse planes of the vertex and the inferior aspects of the feet (Clarys *et al*., 2006). The stretch stature method was used and standing height was measured with a sliding stadiometer (Seca, Germany). The participants were asked to wear shorts and a t-shirt and to stand barefoot on the scale with their heels together. The heels, buttocks and upper part of the back should touch the scale. The head of the player was fixed in the Frankfort position. This is when the orbital (lower edge of the eye socket) and the tragion (the notch superior to the tragus of the ear) are horizontally aligned. The participant was then asked to take a deep breath and the researcher then placed the head board firmly down the vertex, compressing the hair as much as possible. The measurement was then taken to the nearest 0,1 cm. Body mass was measured using a calibrated electronic scale (UWE BW-150, 1997 model, Brisbane, Australia) recorded to the nearest 0,1 kg.

2. Body Composition

Body composition was measured using the BodyMetrix™ ultrasound system, which is a reliable measure for estimating body fat percentage, fat mass and fat free mass. Intra-class correlations for these measures range from 0,84 - 0,98 (Smith-Ryan *et al*., 2014). The device employs the Jackson

and Pollock 7-site protocol (Jackson and Pollock, 1978), with measurements taken at the following anatomical locations as per the manufacturer's recommendations: chest – midway between the anterior axillary line and the nipple; scapula – the lateral side just below the bottom tip of the scapula; axilla – the mid-axillary line, level with the bottom of the sternum; triceps – midway between the acromion and the radiale, on the mid-line of the posterior surface of the arm; waist – 5 cm lateral to the umbilicus; hip – most lateral aspect above the iliac crest; thigh – the anterior midline of the thigh midway between the patella and the crease of the hip. Ultrasound gel (BioEarth Laboratories) was applied to the device before measurement and reapplied before subsequent measurements when necessary. All measurements were conducted on the right side of the body, with 2-3 measurements per site for increased accuracy. A third measurement was taken if the first two differed by more than a single millimetre.

3. Personal Details Form (Appendix B)

The Personal Details form covered participant demographics, such as name, age, hours of sleep, sleep quality, academic programme, sport participation history, current participation and training history. Hours of sleep referred to the number of hours of sleep obtained by the participant for the night prior to testing. Quality of sleep was rated on a 5-point Likert-type scale, with a 5 being optimal quality (heavy sleep throughout the night) and a 1 being lowest quality (constantly waking up, shifting or feelings of discomfort). Details on how to complete the form were given to the participant immediately prior to its completion.

4. Health Screening Questionnaire (Appendix C)

A modified version of the ACSM Medical Screening Questionnaire was used to clear the control group participants for participation. The ACSM questionnaire is in the public domain and was specifically developed for research laboratories such as the Sport Physiology laboratory (American College of Sports Medicine, Lippincott Williams & Wilkins, 2014). Medical clearance for the Rugby group was obtained from the team doctor.

5. Mood state Questionnaire (Appendix D)

The participants completed a version of the Profile of Moods States questionnaire, named the Stellenbosch Mood Scale (STEMS). STEMS is a derivative of the original Profile of Mood Sates (Terry *et al*., 2003) and is dual language (English and Afrikaans). The reliability and validity of STEMS have been reported previously (Terry *et al*., 2003).

The questionnaire covers six mood states (anger, confusion, depression, fatigue, tension, vigour) each made up of four items (giving a total of 24 items). Each item is scored on a 5-point Likert-type scale from 0 (not at all) to 4 (extremely). Each participant was required to complete each item, circling the value that best described how they felt in that moment (Terry *et al.*, 2003). Each mood state was calculated by adding the scores of the four items pertaining to that mood state. Additionally, a total mood disturbance score and energy index was calculated using the following formulae (Kentta *et al.*, 2006):

Total mood disturbance = Vigour - (Tension + Depression + Anger + Fatigue + Confusion)

Energy Index = Vigour - Fatigue

6. Training and Match Time (Appendix E, F and G)

The number of matches and training sessions completed by each rugby player was recorded throughout the season by the researcher who attended the team's practice sessions and viewed the matches via video analysis (Appendix G). The amount of participation time in each of these sessions was also recorded for each participant. Additionally, the type of training was recorded with play categorised into non-contact (NC), semi-contact (SC) and full contact (FC). NC, as defined by the researcher, were drills where the players were instructed to not make contact with opposing players, i.e. skill development, shadowing, set-moves, etc. SC was defined as drills involving the use of tackle bags to reduce the levels of contact, or where the players were instructed to make contact but at levels below that of match intensity. FC was defined as drills where players were instructed to make contact with the opposition at full intensity. Players who frequently participated in 2nd team training sessions were given a separate training diary to fill in (Appendix F). The Control group was responsible for the recording of their training time, using a log-sheet given to them (Appendix E). A significant relationship (r = 0,84) between self-reported training load and recorded training load has been reported previously (Borrenson and Lambert, 2006).

7. Cognitive Testing Battery

The testing battery consisted of computer-based tests selected from the CNS Vital Signs VS4 core software (CNS Vital Signs LLC, Morrisville, North Carolina, USA). The testing battery was performed on a HP EliteBook 8570p laptop (HP Inc., Palo Alto, CA, USA) running off the Windows 10 operating system (Microsoft® Corporation, Redmond, WA, USA). The tests form the CNS Vital Signs Core assessment battery and assess multiple cognitive domains, namely; composite memory, verbal memory, visual memory, psychomotor speed, reaction time, complex attention, cognitive

flexibility, processing speed, executive function, simple attention and motor speed. These tests are not diagnostic tests and the test battery can be administered by non-specialists or non-medical persons.

A summary of the specific tests that make up each domain score can be seen in Table 4.1. The Core battery consists of 7 tests, namely; the Verbal Memory Test (VBM), Visual Memory Test (VIM), Finger Tapping Test (FTT), Symbol digit Coding (SDC), Stroop Test, Shifting Attention Test (SAT) and the Continuous Performance Test (CPT). All of the tests, apart from the Verbal and Visual Memory tests and the Continuous Performance Test, included a short practice trial to familiarise the participant with the test and avoid confusion. The Core testing battery was selected due to it covering cognitive domains similar to those assessed in other studies that examined the effects of repeated mild traumatic brain injury in athletes (Bailey *et al.*, 2013; Dean and Sterr, 2013; Helmich *et al.*, 2015).

Table 4.1. Tests scores contributing to relevant cognitive domain scores

Cognitive Domain	Contributing Test Scores
Composite Memory	VBM + VIM
Verbal Memory	VBM Correct Hits Immediate + VBM Correct Passes Immediate + VBM Correct Hits Delay + VBM Correct Passes Delay
Visual Memory	VIM Correct Hits Immediate + VIM Correct Passes Immediate + VIM Correct Hits Delay + VIM Correct Passes Delay
Psychomotor Speed	FTT Right Taps Average + FTT Left Taps Average + SDC Correct Responses
Reaction Time	(Stroop 2 Reaction Time Correct + Stroop 3 Reaction Time Correct) / 2
Complex Attention	Stroop 3 Errors + SAT Errors + CPT Errors
Cognitive Flexibility	SAT Correct Responses - SAT Errors - Stroop 3 Errors
Processing Speed	SDC Correct Responses - SDC Errors
Executive Function	SAT Correct Responses - SAT Errors
Simple Attention	CPT Correct Responses - CPT Errors
Motor Speed	FTT Right Taps Average + FTT Left Taps Average

VBM, Verbal Memory Test; VIM, Visual Memory Test; FTT, Finger Tapping Test; SDC, Symbol Digit Coding Test; SAT, Shifting Attentions Test; CPT, Continuous Performance Test.

The validity and reliability of the tests have been previously examined and found to be similar to other tests assessing the same functions (Gualtieri and Johnson, 2006). Test-retest reliability was assessed and ranged from r = 0,65 - 0,88 (Gualtieri and Johnson, 2006). The individual tests were as follow:

i) VBM: A list of fifteen words was presented on-screen to the participant. Each word was separated by a period of two seconds. Immediately afterwards the list was presented with an additional fifteen words mixed in and the participant had to identify which words were on the original list. The participants made their selection by pressing the spacebar button on the keyboard. Once all of the subsequent tests in the battery were completed a delayed recall trial took place where the participants once again selected the words that were on the original list.

ii) VIM: Fifteen geometric shapes were presented on-screen to the participant, each separated by two seconds. The participant then had to identify these figures amongst fifteen new figures. Once the remaining tests were completed the participant had to once again identify the shapes amongst fifteen new figures as part of a delayed recall trial. As in the VBM the participants made their selections by pressing the spacebar button on the keyboard.

iii) FTT: The participants had to press the spacebar button as many times as possible in ten seconds with their right index finger. The participants were allowed one practice trial which was followed by three test trials. The test was then repeated with the left hand.

iv) SDC: The participant was presented with a group of eight symbols each matched to a number from 2 to 9. Below there was a bank of eight of the symbols with empty boxes. The participant must type the number that corresponds to each of the symbols. The participant was presented with a series of these banks and had to complete them as accurately and quickly as possible for a period of two minutes.

v) Stroop: There are three parts to the Stroop test. For part 1 the words RED, BLUE, YELLOW and GREEN appeared on the screen at random intervals and the participant had to react and press the spacebar key as fast as possible when each word appeared. For part 2 the same words appeared on the screen at random intervals, however, this time printed in colour. The participant had to press spacebar when the colour of the word matched the name of the word. In part 3 the process was repeated, however, the participant had to press spacebar when the colour *did not* match the name of the word.

vi) SAT: The participant was required to match geometric shapes (a square or circle) based on changing instructions. Three shapes would be presented on the screen, either a square or circle in the top middle of the screen, a circle in the bottom left, and a square in the

bottom right. Each shape was coloured either red or blue. Above the shapes was an instruction that would change with each trial. The instruction would read either “Match Shape” or “Match Colour”. The participant was required to match the bottom shape that corresponded to the top shape based on the instruction given using either the left or right “shift” key.

vii) CPT: The participants were presented with a single letter on the screen that would change at random intervals. The participants were required to respond to only the letter “B” as quickly as possible by pressing the spacebar key. The test lasted five minutes.

8. Cerebral oxygenation

Cerebral oxygenation was measured with a NIRO-200NX Oxiometer (Hamamatsu Photonics, Tokyo, Japan). A photo of the testing set-up including the NIRS measurement graphs can be seen in Figure 4.2.

Figure 4.2. Experimental set-up for cognitive function and cerebral oxygenation measurements. Image provided by the researcher.

Prior to application of the measurement probes the participant’s forehead was cleaned with 70% isopropyl alcohol swabs (Hi-Care $_{INT}$) to remove any substances that may result in interference or noise in the signal. The positioning of the measurement probes was calculated using the international 10-20 system for EEG electrode placement (Jurcak *et al.*, 2007). The light emitters were placed on positions Fp1 and Fp2 for the left and right sides of the forehead, respectively. The detectors were placed between positions F3 and F7 on the left side of the forehead and between F4 and F8 on the right side of the forehead. These positions correspond to Brodmann Area 10 and Brodmann Area 46

in the left and right prefrontal cortex. While measurements were conducted on both sides of the forehead, only the left side was used in analysis. The EEG positions were calculated using the following method:

1) Locate the nasion (bridge of the nose) and inion (occipital protuberance) via palpation of the bony anatomy of the skull.
2) Measure the distance between the two anatomical landmarks. Mark 10% of the total distance between the 2 points on the anterior and posterior aspect on the skull. These points correspond the Fpz (anterior) and Oz (posterior).
3) Mark 20% of the total distance between the nasion and inion above Fpz. This corresponds to Fz.
4) Measure the circumference between Fpz and Oz.
5) Mark 5 % of the total circumference to the left and right of Fpz. These points correspond to Fp1 and Fp2 respectively.
6) Mark an additional 10% of the total circumference to the left and right of Fp1 and Fp2. These positions correspond to F7 and F8.
7) Calculate the distance between F7 and F8. The intersection of half this distance with the first Fz mark represents the true Fz.
8) Measure the distance between F7 and Fz, as well as F8 and Fz. Half the distance between these two measurements corresponds to F3 and F4.

Measurements were taken with a flexible steel Rosscraft Anthrotape (Rosscraft Inc.). The light emitters and detectors were contained within rubber holders provided by the manufacturer, setting the distance between the emitter and detector at 4 cm. The probes were fixed to the scalp using double-sided adhesive tape (Sellotape®). A black elastic headband was then placed around the head to prevent additional external light from affecting the readings. Latex free cohesive strapping (Peha-haft®, Hartman Inc.) of 4 cm diameter was then used to further secure the probes on the scalp and prevent displacement of the set-up. Participants were seated in a comfortable chair for the duration of the measurements to further reduce the risk of probe displacement.

Recordings were done at wavelengths of 735 nm, 810 nm and 850 nm with a sampling rate of 5 hertz (Hz) as determined by the manufacturer. Changes in oxyhaemoglobin concentration ($\Delta[O_2Hb]$), deoxyhaemoglobin concentration ($\Delta[HHb]$), tissue oxygenation index (TOI) and normalised total haemoglobin index (nTHI) were measured continuously throughout baseline, cognitive testing and the recovery period. $\Delta[O_2Hb]$ and $\Delta[HHb]$ were considered as measures of cerebral oxygenation and oxygen consumption, respectively. TOI was considered a measure of regional oxygen saturation while nTHI was considered to reflect changes in cerebral blood flow rate. Both TOI and nTHI are

calculated by the NIRO-200NX Oxiometer using the following formulas given by the manufacturer (Hamamatsu Photonics, Deutschland, 2012):

$$\text{TOI} = \frac{\text{O2Hb}}{\text{O2Hb+HHb}} \times 100$$

nTHI = kO$_2$Hb + kHHb where k is the constant for light scattering.

The beginning and end of each test was marked and the time noted to ensure accuracy of start and end times during data analysis. Oxygenation data was filtered by manually removing error artefacts using the Microsoft Excel 2016 "find and replace" function (Windows®, 2016, USA). The data was then averaged for the duration of each test and the final minute of the baseline and recovery phase. Relative values were then calculated by subtracting the baseline value from all subsequent zones. Relative values from baseline, recovery and the final testing phase were used for analysis (see Chapter Five Section E).

E. Statistical Analysis

Statistical analysis of the data was performed using Microsoft Excel 2016 (Windows®, 2016, USA) and STATISTICA® 13.2 (Statsoft, 2013, USA). All descriptive statistics are reported as means and standard deviations (SD), or confidence intervals. Cerebral oxygenation data was screened for normality of distribution and homogeneity with the Levene's and Shapiro-Wilk normality tests. Paired t-tests were used to analyse within-group differences (pre- to post-testing changes) of the two groups for all the outcome variables. Unpaired t-tests were used to compare between-group differences for the changed scores of the outcome variables. Additionally, Cohen's effect sizes (ES) were calculated to infer magnitude-based differences for all outcome variables with the use of 95% confidence intervals. The following thresholds proposed by Hopkins and colleagues was used to interpret effect size (Hopkins *et al*., 2009): Small (≥ 0,2 and < 0,6), Moderate (≥ 0,6 and < 1,2) and Large (≥ 1,2 and < 2). Pearson's correlation coefficients were used to determine the relationships between changes in sleep, mood state, cognitive function and cerebral oxygenation. Confidence intervals (95%) were calculated for the correlations using an Excel sheet developed by Hopkins, 2002. Thresholds of 0,3, 0,5, 0,7 and 0,9 were interpreted as small, moderate, high and very high correlations, respectively (Mukaka, 2012).

G*Power 3.1.9.2 was used to calculate the study sample size. Cohen's effect sizes were calculated from studies by Richardson *et al.* (2017) and Bailey *et al.* (2013). Assuming a power of 95% and a 5% level of significance, it was calculated that a sample size of n = 18 - 22 (total) would be needed to detect a moderate practical significant difference in ECF and cerebral oxygenation between rugby

players and non-contact sportpersons who are matched for age. Cerebral oxygenation data were further analysed using a mixed model repeated measures analysis of variance (ANOVA). GROUP and TIME were treated as fixed effects and the participants as random effects. Fisher's least significant difference post hoc tests were included to determine differences in treatment effects between groups. In all cases statistical significance was set at $P < 0,05$.

CHAPTER FIVE

RESULTS

A. Participants

Thirty-nine (39) participants (24 rugby players and 15 non-contact sport athletes) volunteered to participate in the study. Those who met the inclusion criteria (39) were split into a Rugby (rugby players) and Control (non-contact athletes) group. Three Rugby participants withdrew prior to testing; one due to travel issues, one due to personal reasons and the other received an injury diagnosis that made him ineligible for participation. Over the course of the study period five rugby players and two control athletes withdrew from the study. Two of the rugby players suffered serious injuries that removed them from play, two suffered concussions and another missed several weeks due to personal reasons. Two control athletes declined to participate in post-testing due to personal reasons.

The remaining 29 participants completed all testing with the Rugby group consisting of 16 participants and the Control group, 13 participants. However, one of the control participants reported being red-green colour blind and thus his results for the Stroop Test and associated domains were excluded, despite him completing all the tests.

Participant details may be seen in Table 5.1. All Rugby participants were members of Stellenbosch University's 1st team squad and had been a member of the 1st or 2nd team for an average of 2,06 ± 1,61 yrs. Participants in the Control group were university students drawn from a variety of sports, namely; hockey (n = 5), squash (n = 3), tennis (n = 1), cricket (n = 1), triathlon (n = 1), athletics (n = 1) and crossfit (n = 1). The highest level of participation in the Control group included club (n = 3), junior provincial (n = 3), provincial (n = 3) and national (n = 4). The Control group was significantly lighter (P = 0,002; ES = 1,27) than the Rugby group. The groups did not differ significantly in age, height or body fat percentage (P > 0,05).

Table 5.1. Between-group comparisons for participant details. Results are presented as mean ± SD.

Characteristic	Rugby	Control	Mean Diff. [95% CI]	ES [95% CI]	P - value
Age (years)	21,3 ± 1,35	20,8 ± 1,97	0,54 [-0,72 ; 1,81]	0,33 [-0,42 ; 1,06]	0,37
Height (cm)	182,2 ± 6,35	177,6 ± 5,72	4,60 [-0,06 ; 9,25]	0,76 [-0,02 ; 1,49]	0,05
Body Mass (kg)	94,3 ± 12,92	79,1 ± 10,52	15,15 [6,02 ; 24,27]	1,27 [0,44 ; 2,03]	0,002
Body Fat Percentage (%)	11,7 ± 3,89	11,3 ± 3,92	0,40 [-2,59 ; 3,39]	0,10 [-0,63 ; 0,83]	0,79
Maties 1st Team (years)	2,1 ± 1,61	-	-	-	-

Significant differences (P < 0,05). Mean Diff, Mean difference; CI, Confidence interval; ES, Effect Size.

B. Training and Sleep

1. Training

A summary of the participants' training and match data is depicted in Table 5.2 and Table 5.3. Training for the Rugby group was monitored over a period of 15 weeks, starting from 9 January 2017 to 23 April 2017. The average time between testing for each rugby player was 13,44 ± 1,02 weeks. Training phases consisted of the preseason (9 January to 29 January) and competition season (30 January to 23 April). During this time, the team participated in a total of 12 matches, two in the preseason period and 10 in the competition period. Additionally, members of the squad (n = 6) who were often interchanged with the 2nd team participated in a total of four league matches, while two members of the squad participated in an additional game for the junior national team and local provincial team, respectively. Training comprised predominantly of semi-contact sessions, which made up 72,3% of the total training time (excluding matches). On average, the players participated in 7,3 ± 3,23 h of match-play, which accounted for 8,7% of total playing time.

Training for the Control group was monitored for an average of 12,66 ± 1,58 weeks. The Control group participated in significantly less practice time (P < 0,0001; ES = 3,08) and total playing time (P < 0,0001; ES = 2,83) than the Rugby group. There were no statistically significant differences in match/competition number or time (hours) spent in competition (P > 0,05).

2. Sleep

There was no statistically significant or qualitative change in the number of hours and quality of sleep in the Rugby group from pre- to post-testing (P > 0,05). There was a moderate practically significant decrease (ES = -0,52) in the number of hours slept from pre- to post-testing in the Control group, however, their quality of sleep was not compromised at the time of post-testing. The between-group differences for the change in hours slept and sleep quality were not statistically significant (P > 0,05). However, group mean differences in sleep quantity exhibited small practically significant differences (ES = 0,35).

Table 5.2. Between-group comparisons for the number of training sessions and matches. Results are presented as mean ± SD.

Number of Sessions					
Type of Session	**Rugby**	**Control**	**Mean Diff. [95% CI]**	**ES [95% CI]**	**P - Value**
Non-Contact	7,9 ± 2,22	-	-	-	-
Semi-Contact	39,6 ± 6,65	-	-	-	-
Full-Contact	3,6 ± 1,73	-	-	-	-
Scrum	4,3 ± 4,85	-	-	-	-
Match/Competition	7,2 ± 2,49	5,9 ± 6,84	1,26 [-2,51 ; 5,04]	0,26 [-0,48 ; 0,98]	0,50
Total Practice Sessions	55,3 ± 9,71	36,0 ± 15,95	19,34 [9,49 ; 29,20]	1,50 [0,64 ; 2,24]	0,0004
Total Playing Sessions	62,5 ± 10,26	41,9 ± 15,92	20,61 [10,49 ; 30,63]	1,58 [0,70 ; 2,36]	0,0002

Significant differences (P < 0,05). Mean Diff, Mean difference; CI, Confidence interval; ES, Effect Size.

Table 5.3. Between-group comparisons for time spent training and playing matches. Results are presented as mean ± SD.

Time of Sessions (hours)					
Type of Session	**Rugby**	**Control**	**Mean Diff. [95% CI]**	**ES [95% CI]**	**P - Value**
Non-Contact	10,4 ± 3,39	-	-	-	
Semi-Contact	55,2 ± 9,69	-	-	-	
Full-Contact	5,7 ± 2,95	-	-	-	
Scrum	5,0 ± 5,71	-	-	-	
Match/Competition	7,3 ± 3,23	6,8 ± 6,84	0,46 [-3,49 ; 4,42]	0,09 [-0,64 ; 0,82]	0,81
Total Practice Sessions	76,3 ± 12,49	39,3 ± 11,36	36,99 [27,79 ; 46,18]	3,08 [1,93 ; 4,06]	< 0,0001
Total Playing Sessions	83,6 ± 12,89	46,1 ± 13,60	37,45 [27,33 ; 47,57]	2,83 [1,74 ; 3,77]	< 0,0001

Significant differences (P < 0,05). Mean Diff, Mean difference; CI, Confidence interval; ES, Effect Size.

Table 5.4. Within-group changes in sleep quantity and quality from pre- to post-testing. Results are presented as mean ± SD.

Rugby						
Sleep	**Pre**	**Post**	**Mean Diff. [95% CI]**	**ES [95% CI]**	**Qualitative Outcome**	**P-Value**
No. Hours	7,9 ± 0,96	7,9 ± 1,03	0,0 [-0,72 ; 0,72]	0,00 [-0,69 ; 0,69]	N	1,00
Quality (a.u)	3,8 ± 0,54	3,9 ± 0,54	0,13 [- 0,27 ; 0,52]	0,23 [-0,47 ; 0,92]	S	0,50
Control						
Sleep	**Pre**	**Post**	**Mean Diff. [95% CI]**	**ES [95% CI]**	**Qualitative Outcome**	**P-Value**
No. Hours	7,7 ± 0,77	7,2 ± 0,86	-0,42 [-1,08 ; 0,24]	-0,52 [-1,28 ; 0,28]	M	0,20
Quality (a.u)	3,9 ± 0,49	4,0 ± 0,91	0,08 [-0,52 ; 0,67]	0,10 [-0,67 ; 0,87]	N	0,79

Mean Diff, Mean difference; CI, Confidence interval; ES, Effect Size; N, No effect; S, Small effect; M, Moderate effect; L, Large effect; VL, Very large effect.

C. Mood State

The within-group changes in the participants' mood state scores are summarised in Table 5.5, while between-group differences for the changes in mood state scores are summarised in Table 5.6 and depicted in Figure 5.1. There were no statistically significant changes in mood scores from pre- to post-testing across all domains in either group (P > 0,05). However, the rugby players reported practically significant stronger feelings of confusion (ES = 0,67) and greater tension (ES = 0,34), but reduced fatigue (ES = -0,38), during post-testing. The Rugby group also reported a small practically significant increase in energy index (ES = 0,39). The Control group experienced small practically significant decreases in confusion (ES = -0,20) and depression (ES = -0,41) during post-testing, but no change in energy index (ES = -0.12).

There were no statistically significant differences between the groups from pre-to post-testing (P > 0,05). However, the rugby players reported a greater degree of confusion (ES = 0,61), depression (ES = 0,44), but less fatigue (ES = -0,45) than the control group during post-testing. Additionally, the Rugby group reported a small practically significant increase in their energy index (ES = 0,42) at post-testing relative to the Control group. The Control group also experienced a small practically significant decrement in feelings of vigour during post-testing (ES = 0,30).

Table 5.5. Within-group changes in the Stellenbosch Mood Scale scores from pre- to post-testing. Results are presented as mean ± SD.

Rugby						
Mood State (a.u)	**Pre**	**Post**	**Mean Diff. [95% CI]**	**ES [95% CI]**	**Qualitative Outcome**	**P-Value**
Anger	1,0 ± 1,32	0,9 ± 1,75	-0,13 [-1,24 ; 0,99]	-0,08 [-0,77 ; 0,61]	N	0,82
Confusion	0,4 ± 0,89	1,3 ± 1,62	0,88 [-0,07 ; 1,82]	0,67 [-0,06 ; 1,36]	M	0,10
Depression	0,8 ± 1,61	1,0 ± 1,21	0,25 [-0,78 ; 1,28]	0,18 [-0,52 ; 0,87]	N	0,62
Fatigue	5,9 ± 3,73	4,5 ± 3,90	-1,44 [-4,19 ; 1,32]	-0,38 [-1,07 ; 0,33]	S	0,30
Tension	0,6 ± 0,89	1,2 ± 2,20	0,56 [-0,65; 1,77]	0,34 [-0,37 ; 1,02]	S	0,35
Vigour	8,8 ± 3,49	9,4 ± 3,10	0,63 [-1,76 ; 3,01]	0,19 [-0,51 ; 0,88]	N	0,60
Total Mood Disturbance	**0,1 ± 7,16**	**0,6 ± 9,47**	**0,50 [-5,56 ; 6,56]**	**0,06 [-0,77 ; 0,61]**	**N**	**0,87**
Energy Index	**2,9 ± 5,34**	**4,9 ± 5,18**	**2,06 [-1,74 ; 5,86]**	**0,39 [-0,06 ; 1,36]**	**S**	**0,28**
Control						
Mood State (a.u)	**Pre**	**Post**	**Mean Diff. [95% CI]**	**ES [95% CI]**	**Qualitative Outcome**	**P-Value**
Anger	0,7 ± 1,38	0,5 ± 1,13	-0,15 [-1,17 ;0,86]	-0,12 [-0,89 ; 0,65]	N	0,76
Confusion	1,1 ± 1,12	0,8 ± 1,21	-0,23 [-1,17 ; 0,71]	-0,20 [-0,96 ; 0,58]	S	0,62
Depression	0,5 ± 1,20	0,1 ± 0,55	-0,38 [-1,14 ; 0,37]	-0,41 [-1,18 ; 0,38]	S	0,30
Fatigue	4,0 ± 2,58	4,0 ± 2,83	0,00 [-2,19 ; 2,19]	0,00 [-0,77 ; 0,77]	N	1,00
Tension	1,8 ± 2,42	1,9 ± 3,23	0,15 [-2,16 ; 2,46]	0,05 [-0,72 ; 0,82]	N	0,89
Vigour	10,1 ± 2,18	9,5 ± 3,55	-0,54 [-2,92 ; 1,85]	-0,18 [-0,95 ; 0,59]	N	0,65
Total Mood Disturbance	**2,0 ± 5,76**	**2,1 ± 8,13**	**-0,08 [-5,63 ; 5,78]**	**0,01 [-0,76 ; 0,78]**	**N**	**0,98**
Energy Index	**6,1 ± 3,35**	**5,5 ± 5,25**	**-0,54 [-4,11 ; 3,03]**	**-0,12 [-0,89 ; 0,65]**	**N**	**0,76**

Mean Diff, Mean difference; CI, Confidence interval; ES, Effect Size; N, No effect; S, Small effect; M, Moderate effect; L, Large effect; VL, Very large effect.

Table 5.6. Between-group comparisons for the changes in Stellenbosch Mood Scale scores from pre- to post-testing. Results are presented as mean ± SD.

Mood State (a.u)	**Rugby**	**Control**	**Mean Diff. [95% CI]**	**ES [95% CI]**	**Qualitative Outcome**	**P-Value**
Anger	-0,13 ± 2,13	-0,15 ± 1,21	0,03 [-1,33 ; 1,39]	0,02 [-0,72 ; 0,75]	N	0,97
Confusion	0,88 ± 1,89	-0,23 ± 1,74	1,11 [-0,29 ; 2,50]	0,61 [-0,16 ; 1,34]	M	0,12
Depression	0,25 ± 1,81	-0,38 ± 0,77	0,63 [-0,47 ; 1,74]	0,44 [-0,31 ; 1,17]	S	0,25
Fatigue	-1,44 ± 3,01	0,00 ± 3,42	-1,44 [-3,89 ; 1,01]	-0,45 [-1,18 ; 0,30]	S	0,24
Tension	0,56 ± 2,22	0,15 ± 2,48	0,41 [-1,38 ; 2,20]	0,17 [-0,56 ; 0,90]	N	0,64
Vigour	0,63 ± 4,18	-0,54 ± 3,55	1,16 [-1,83 ; 4,16]	0,30 [-0,45 ; 1,02]	S	0,43
Total Mood Disturbance	**0,5 ± 9,68**	**0,1 ± 7,80**	**0,42 [-6,39 ; 7,24]**	**0,05 [-0,69 ; 0,78]**	**N**	**0,90**
Energy Index	**2,1 ± 6,33**	**-0,5 ± 5,92**	**2,60 [-2,11 ; 7,31]**	**0,42 [-0,33 ; 1,15]**	**S**	**0,27**

Mean Diff, Mean difference; CI, Confidence interval; ES, Effect Size; N, No effect; S, Small effect; M, Moderate effect; L, Large effect; VL, Very large effect.

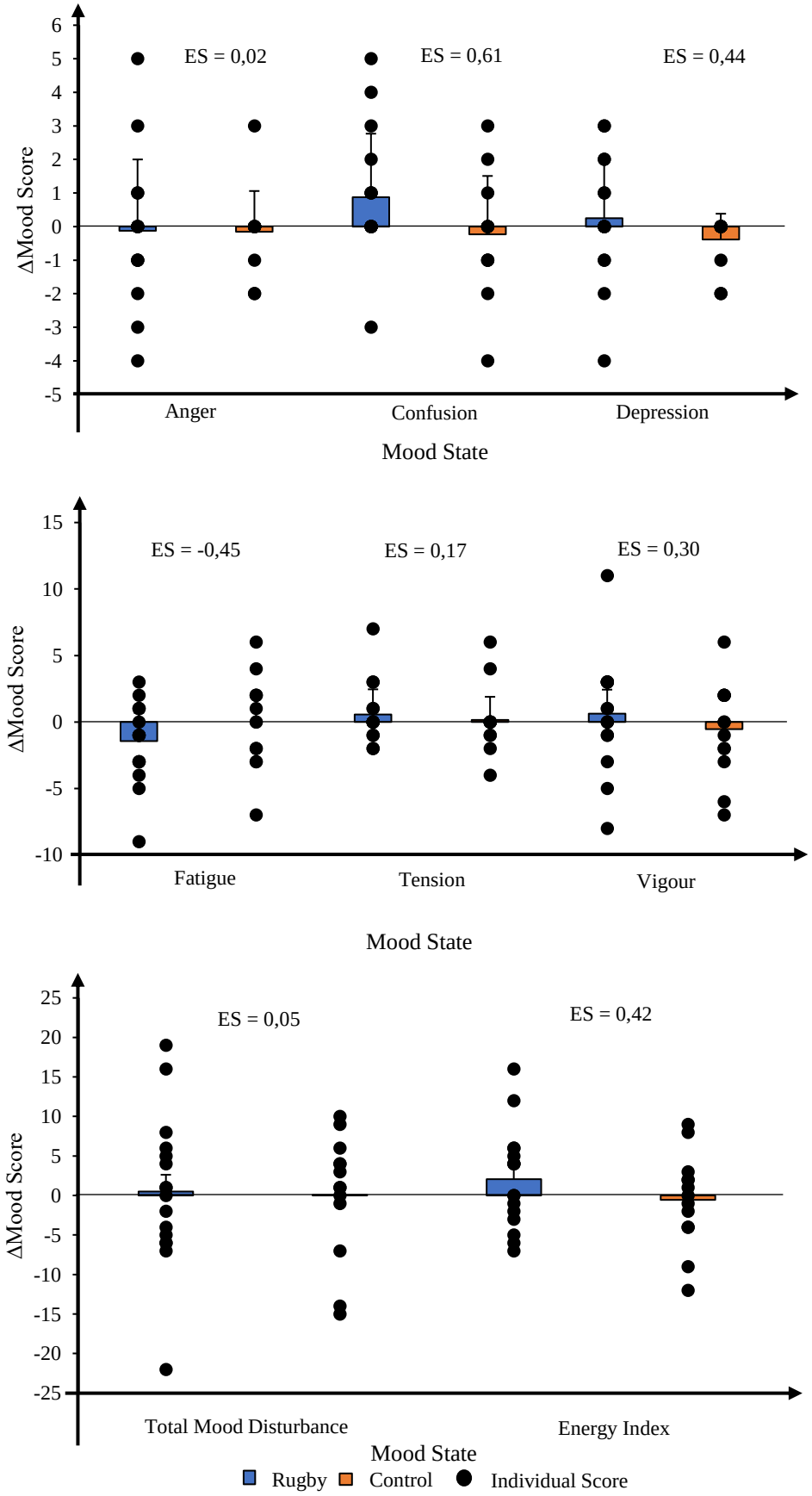


Figure 5.1. Between-group comparisons for the changes in Stellenbosch Mood Scale scores from pre- to post-testing. Dots indicate individual data points. Columns indicate group mean ± SD.

D. Cognitive Function

The cognitive domain scores were calculated using scores of the various tests in the CNS Vital Signs Core testing battery which may be seen in Appendix H. The neurocognitive index of each participant was calculated by averaging the standardised scores of each cognitive domain. The within-group changes in the participants' cognitive domain scores are summarised in Table 5.7, while between-group differences for the change in cognitive domain scores are summarised in Table 5.8 and depicted in Figures 5.2 to 5.7.

There were no statistically significant changes for both groups in cognitive domain scores from pre- to post-testing across all the cognitive domains, including the neurocognitive index ($P > 0,05$). However, the Rugby group exhibited small practically significant increases in cognitive flexibility (4,19%; ES = 0,25), psychomotor speed (3,45%; ES = 0,47) and processing speed (6,88%; ES = 0,40), but decreased performance in the domains of visual memory (2,13%; ES = -0,23) and simple attention (0,79%; ES = -0,26). The Control group experienced practically significant increases in the domains of cognitive flexibility (8,82%; ES = 0,53) and executive function (12,12%; ES = 0,77), but decreased performance in composite (3,12%; ES = -0,63) and verbal (3,13%; ES = -0,50) memory. Additionally, the Control group experienced small practically significant increases in reaction time (2,09%; ES = 0,26) and processing speed (2,84%; ES = 0,21) and a worse performance in visual memory (3,12%; ES = -0,43).

There were no statistically significant differences between the groups from pre-to post-testing ($P > 0,05$). However, the Rugby group experienced practically significant greater improvements in cognitive domains involving information processing and motor skills, namely; psychomotor speed (ES = 0,30), processing speed (ES = 0,25) and motor speed (ES = 0,27). The Control group performed practical significantly better in the "higher" cognitive domains of cognitive flexibility (ES = -0,31) and executive function (ES = -0,67), but worse in measures of memory (ES = -0,31).

Table 5.7. Within-group changes in CNS Vital Signs cognitive domain scores from pre- to post-testing. Results are presented as mean ± SD.

Rugby						
Cognitive Domain	**Pre**	**Post**	**Mean Diff. [95% CI]**	**ES [95% CI]**	**Qualitative Outcome**	**P-Value**
Composite Memory	104 ± 5,92	102,9 ± 7,27	-1,13 [-5,91 ; 3,66]	-0,17 [-0,86 ; 0,53]	N	0,63
Verbal Memory	54,3 ± 3,34	54,2 ± 3,17	-0,06 [- 2,41 ; 2,29]	-0,02 [- 0,71 ; 0,67]	N	0,96
Visual Memory	49,8 ± 4,25	48,7 ± 5,07	-1,06 [-4,44 ; 2,32]	-0,23 [-0,92 ; 0,47]	S	0,53
Psychomotor Speed	188,4 ± 14,9	194,9 ± 12,67	6,50 [-3,49 ; 16,49]	0,47 [-0,24 ; 1,16]	S	0,19
Reaction Time*(ms)	622,4 ± 93,46	626,9 ± 95,23	4,44 [-63,69 ; 72,56]	0,05 [-0,65 ; 0,74]	N	0,90
Complex Attention*	9,2 ± 3,41	8,8 ± 4,74	-0,44 [-3,42 ; 2,54]	-0,11 [-0,80 ; 0,59]	N	0,77
Cognitive Flexibility	47,7 ± 7,55	49,7 ± 8,38	2,00 [-3,76 ; 7,76]	0,25 [-0,45 ; 0,94]	S	0,48
Processing Speed	59 ± 9,67	63,1 ± 10,41	4,06 [-3,19 ; 11,32]	0,40 [-0,31 ; 1,09]	S	0,26
Executive Function	50,5 ± 7,14	51,4 ± 8,70	0,94 [-4,81 ; 6,68]	0,12 [-0,58 ; 0,81]	N	0,74
Simple Attention	39,2 ± 1,17	38,9 ± 1,26	-0,31 [-1,19 ; 0,56]	-0,26 [-0,95 ; 0,44]	S	0,47
Motor Speed	127,7 ± 13,71	129,8 ± 10,19	2,13 [-6,60 ; 10,85]	0,18 [-0,52 ; 0,87]	N	0,62
Neurocognitive Index	**98,8 ± 8,44**	**99,8 ± 8,64**	**0,94 [-5,23 ; 7,10]**	**0,11 [-0,59 ; 0,80]**	**N**	**0,76**
Control						
Cognitive Domain	**Pre**	**Post**	**Mean Diff. [95% CI]**	**ES [95% CI]**	**Qualitative Outcome**	**P-Value**
Composite Memory	108,5 ± 4,40	105,2 ± 6,22	-3,38 [-7,76 ; 0,99]	-0,63 [-1,39 ; 0,18]	M	0,12
Verbal Memory	56,6 ± 2,6	54,8 ± 4,28	-1,77 [-4,64 ; 1,11]	-0,50 [-1,26 ; 0,30]	S	0,22
Visual Memory	51,9 ± 4,00	50,3 ± 3,43	-1,62 [-4,64 ; 1,41]	-0,43 [-1,20 ; 0,36]	S	0,28
Psychomotor Speed	186,6 ± 20,20	189,7 ± 16,78	3,08 [-11,96 ; 18,11]	0,17 [- 0,61 ; 0,93]	N	0,68
Reaction Time*(ms)	567,3 ± 49,80	579,2 ± 37,56	11,83 [-25,49 ; 49,15]	0,27 [-0,54 ; 1,06]	S	0,52
Complex Attention*	7,8 ± 3,50	7,23 ± 2,61	-0,50 [-2,99 ; 1,99]	-0,17 [-0,97 ; 0,64]	N	0,68
Cognitive Flexibility	50,1 ± 9,10	54,5 ± 7,31	4,42 [-2,59 ; 11,43]	0,53 [-0,30 ; 1,33]	S	0,20
Processing Speed	65,2 ± 8,40	67 ± 9,19	1,85 [-5,30 ; 8,99]	0,21 [-0,57 ; 0,97]	S	0,60
Executive Function	51,2 ± 9,10	57,4 ± 7,07	6,23 [-0,36 ; 12,82]	0,77 [-0,05 ; 1,54]	M	0,06
Simple Attention	39,7 ± 0,90	39,7 ± 0,63	0,00 [-0,61 ; 0,61]	0, 00 [-0,77 ; 0,77]	N	1,00
Motor Speed	120,2 ± 14,2	119,9 ± 12,02	-0,31 [-10,96 ; 10,34]	-0,02 [-0,79 ; 0,75]	N	0,95
Neurocognitive Index	**105,3 ± 8,09**	**105,8 + 6,43**	**0,42 [-5,5- ; 6,33]**	**0,06 [-0,71 ; 0,82]**	**N**	**0,89**

Lower score indicates better performance. Mean Diff, Mean difference; CI, Confidence interval; ES, Effect Size; N, No effect; S, Small effect; M, Moderate effect; L, Large effect; VL, Very large effect.

Table 5.8. Between-group comparisons for the changes in CNS Vital Signs cognitive domain scores from pre- to post-testing. Results are presented as mean + SD.

Cognitive Domain	Rugby	Control	Mean Diff. [95% CI]	ES [95% CI]	Qualitative Outcome	P-Value
Composite Memory	-1,13 ± 7,86	-3,38 ± 4,61	2,26 [-2,81 ; 7,33]	0,34 [-0,41 ; 1,07]	S	0,37
Verbal Memory	-0,06 ± 4,09	-1,77 ± 3,98	1,71 [-1,39 ; 4,80]	0,42 [-0,33 ; 1,15]	S	0,27
Visual Memory	-1,06 ± 5,13	-1,62 ± 3,62	0,55 [-2,91 ; 4,02]	0,12 [-0,61 ; 0,85]	N	0,75
Psychomotor Speed	6,50 ± 10,51	3,08 ± 12,30	3,42 [-5,26 ; 12,11]	0,30 [-0,44 ; 1,03]	S	0,43
Reaction Time*(ms)	4,44 ± 54,26	11,83 ± 28,73	-7,40 [-42,92 ; 28,12]	-0,16 [-0,91 ; 0,59]	N	0,67
Complex Attention*	-0,44 ± 3,97	-0,50 ± 3,78	0,06 [-2,99 ; 3,11]	0,02 [-0,73 ; 0,76]	N	0,97
Cognitive Flexibility	2,00 ± 5,89	4,42 ± 9,67	-2,42 [-8,48 ; 3,64]	-0,31 [-1,06 ; 0,45]	S	0,42
Processing Speed	4,06 ± 8,74	1,85 ± 9,33	2,22 [-4,68 ; 9,12]	0,25 [-0,50 ; 0,97]	S	0,52
Executive Function	0,94 ± 5,54	6,23 ± 10,16	-5,29 [-11,37 ; 0,78]	-0,67 [-1,40 ; 0,10]	M	0,09
Simple Attention	-0,31 ± 1,45	0,00 ± 0,91	-0,31 [-1,26 ; 0,64]	-0,25 [-0,98 ; 0,49]	S	0,51
Motor Speed	2,13 ± 9,49	-0,31 ± 8,58	2,43 [-4,53 ; 9,40]	0,27 [-0,47 ; 0,99]	S	0,48
Neurocognitive Index	**0,94 ± 7,01**	**0,42 ± 5,04**	**0,52 [-4,24 ; 5,28]**	**0,08 [-0,65 ; 0,81]**	**N**	**0,82**

* Lower score indicates better performance. Mean Diff, Mean difference; CI, Confidence interval; ES, Effect Size; N, No effect; S, Small effect; M, Moderate effect; L, Large effect; VL, Very large effect.

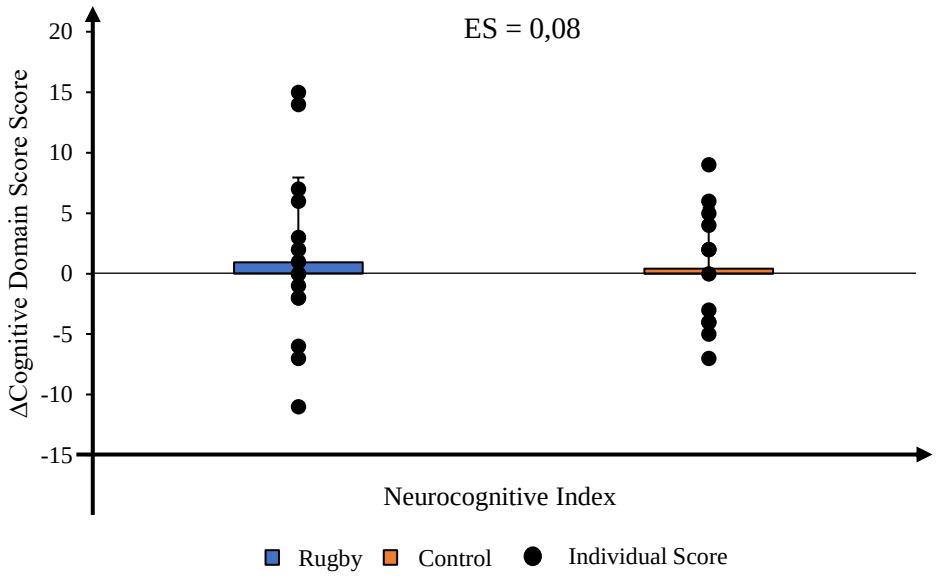


Figure 5.2. Change in neurocognitive index score from pre- to post-testing. ES, Effect Size. Dots indicate individual data points. Columns indicate group mean ± SD.

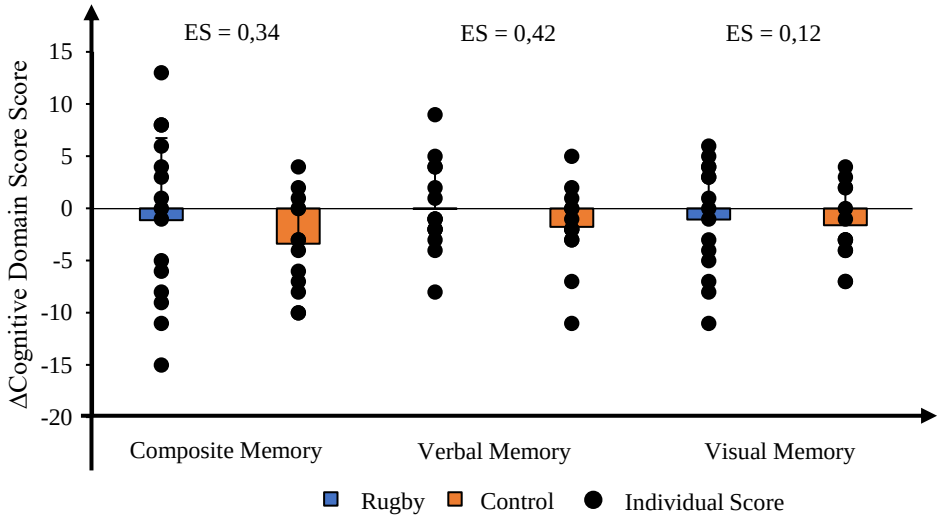


Figure 5.3. Change in cognitive domain scores of composite memory, verbal memory and visual memory. ES, Effect Size. Dots indicate individual data points. Columns indicate group mean ± SD.

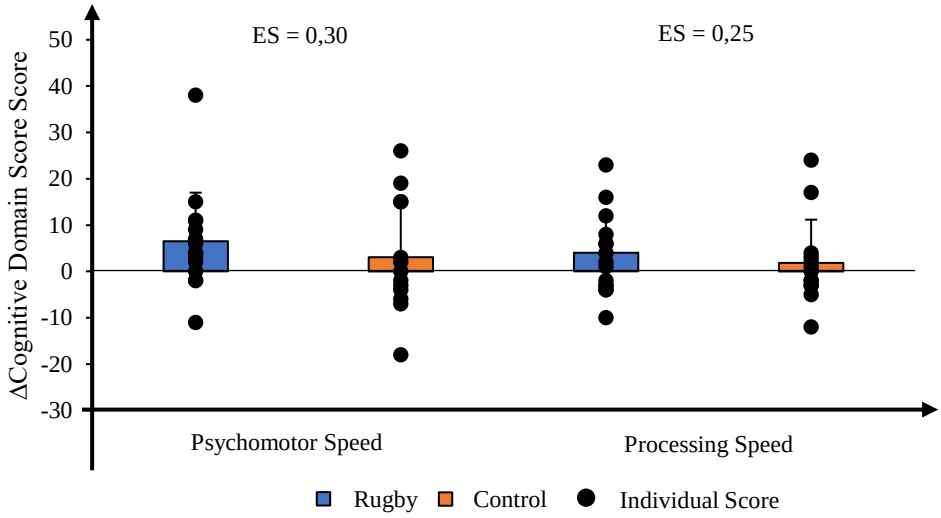


Figure 5.4. Change in cognitive domain scores of Psychomotor Speed and Processing Speed. ES, Effect Size. Dots indicate individual data points. Columns indicate group mean ± SD.

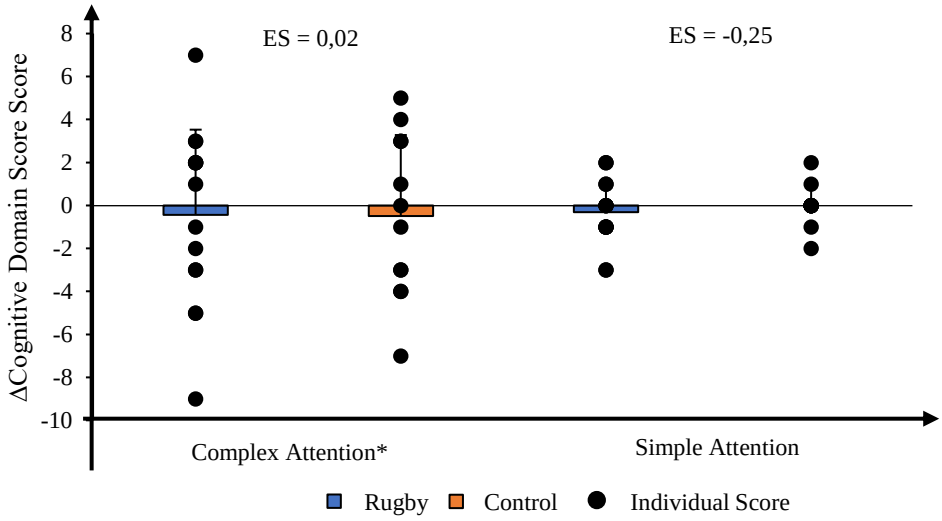


Figure 5.5. Change in cognitive domain scores of Complex Attention and Simple Attention. *Lower score indicates improved performance. ES, Effect Size. Dots indicate individual data points. Columns indicate group mean ± SD.

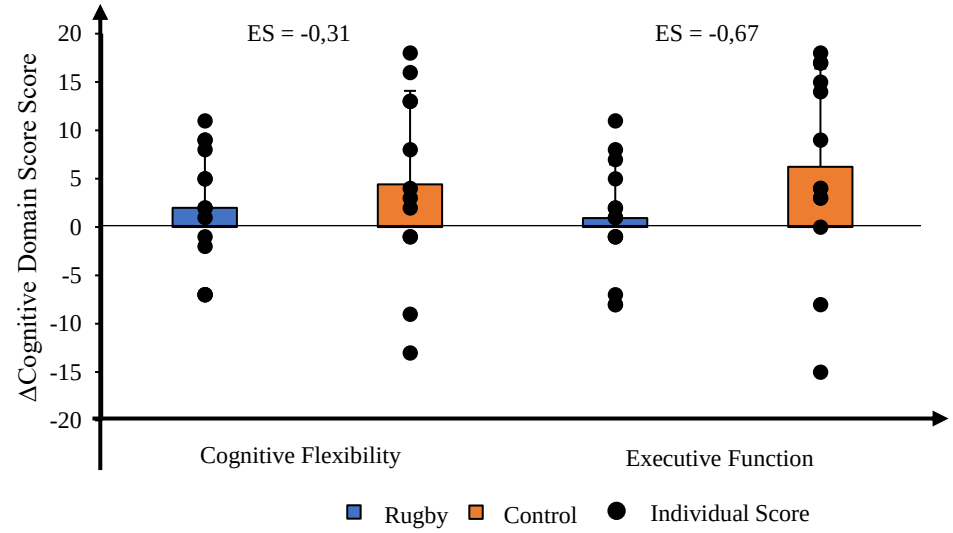


Figure 5.6. Change in cognitive domain score of Cognitive Flexibility and Executive Function. ES, Effect Size. Dots indicate individual data points. Columns indicate group mean ± SD.

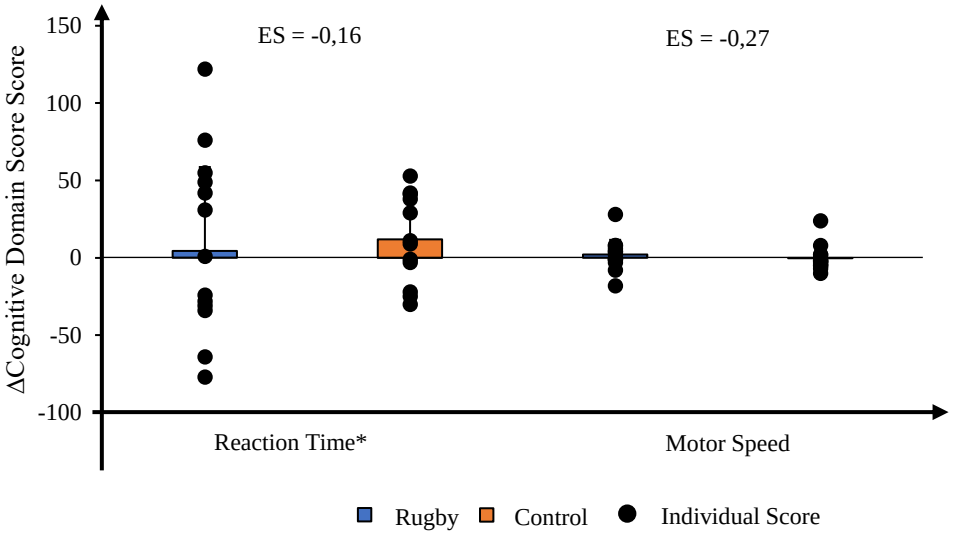


Figure 5.7. Change in cognitive domain score of Reaction Time and Motor Speed. *Lower score indicates improved performance. ES, Effect Size. Dots indicate individual data points. Columns indicate group mean ± SD.

E. Cerebral Oxygenation

The global changes in oxyhaemoglobin concentration Δ[O_2Hb] and the relevant zones can be seen in Figure 5.8.1 and 5.8.2. Cerebral oxygenation variables in the left prefrontal cortex (LPFC) were measured continuously using near-infrared spectroscopy (NIRS) during (a) the five-minute baseline period preceding cognitive testing, (b1-2) cognitive testing battery and (c) during a 5-minute recovery period following the final cognitive test. Mean changes were calculated over the final minute of the Baseline (Figure 5.8.a), Cognitive Testing (Figure 5.8.b2) and Recovery (Figure 5.8.c) periods and used for analysis. Relative changes in oxyhaemoglobin concentration (Δ[O_2Hb]), deoxyhaemoglobin concentration (Δ[HHb]), tissue oxygenation index (TOI) and normalised total haemoglobin index (nTHI) were then calculated by subtracting Baseline (a) from the Cognitive Testing (b2) and Recovery (c) periods. Results for the relative changes during the Cognitive Testing and Recovery periods are presented below.

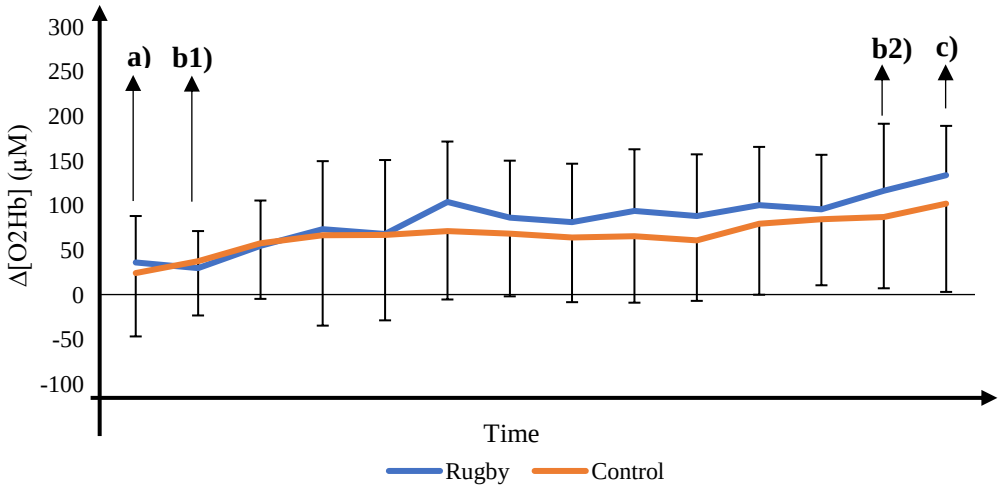


Figure 5.8.1. Global oxyhaemoglobin concentration (Δ[O_2Hb]) during **pre-testing** with the relevant zones, namely **a) Baseline**, **b1) Start of cognitive testing battery, b2) Cognitive Testing**, **c) Recovery**.

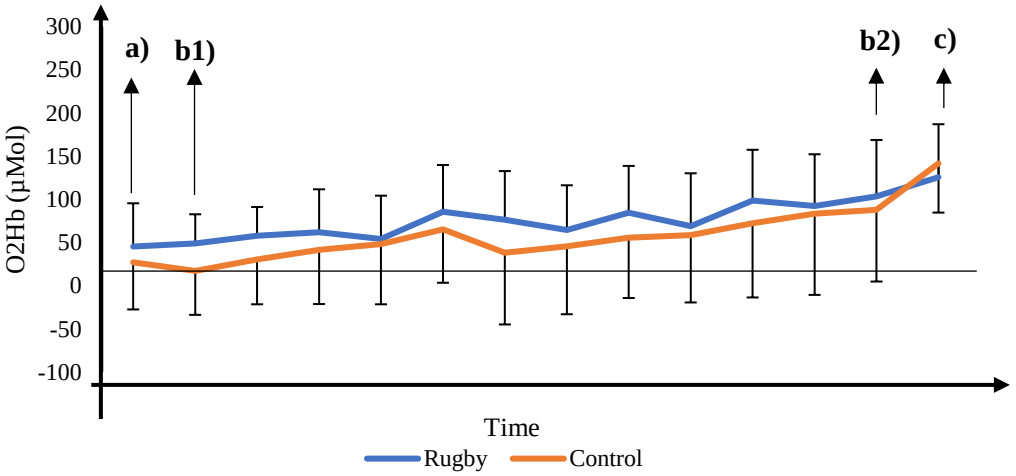


Figure 5.8.2. Global oxyhaemoglobin concentration (Δ[O_2Hb]) during **post-testing** with the relevant zones, namely **a) Baseline**, **b1) Start of cognitive testing battery, b2) Cognitive Testing**, **c) Recovery**.

1. Oxyhaemoglobin (O_2Hb)

Within-group changes in the participants' relative O_2Hb concentration ($\Delta[O_2Hb]$) are summarised in Table 5.9, while between-group differences for the change in relative $\Delta[O_2Hb]$ are summarised in Table 5.10. and depicted in Figure 5.9. Regarding the global changes both groups experienced a statistically significant increase in global $\Delta[O_2Hb]$ from Baseline during Cognitive Testing ($P = 0,001$) and Recovery ($P < 0,0001$) (exhibited by positive relative values), at pre- and post-testing.

There were no statistically significant differences in relative $\Delta[O_2Hb]$ from pre- to post-testing across both measurement zones ($P > 0,05$). However, the Rugby group showed small practically significant decreases in $\Delta[O_2Hb]$ during Cognitive Testing (ES = -0,28) and Recovery (ES = -0,27) with post-testing. In the Control group, the relative $\Delta[O_2Hb]$ remained at similar levels during Cognitive Testing but exhibited a small practically significant increase of (ES = 0,57) during Recovery at post-testing.

GROUP × TIME analysis revealed that there were no statistically significant interaction effects ($P > 0,05$). However, the mean difference between-groups indicated that the Rugby group exhibited small practically significant decreases relative to the Control group during Cognitive Testing (ES = -0,22) and Recovery (ES = -0,59) at post-testing.

Table 5.9. Within-group changes in relative oxyhaemoglobin concentration ($\Delta[O_2Hb]$) (µM) from pre- to post-testing. Results are presented as mean ± SD.

Rugby						
Measurement Period	**Pre**	**Post**	**Mean Diff. [95% CI]**	**ES [95% CI]**	**Qualitative Outcome**	**P-Value**
Cognitive Testing	80,5 ± 79,27	58,0 ± 79,45	-22,49 [-79,79 ; 34,81]	-0,28 [-0,97 ; 0,42]	S	0,43
Recovery	97,8 ± 51,51	80,2 ± 77,50	-17,54 [-65,05 ; 29,97]	-0,27 [-0,96 ; 0,44]	S	0,46
Control						
Measurement Period	**Pre**	**Post**	**Mean Diff. [95% CI]**	**ES [95% CI]**	**Qualitative Outcome**	**P-Value**
Cognitive Testing	62,9 ± 54,63	60,5 ± 67,54	-2,39 [-52,12 ; 47,34]	-0,04 [-0,81 ; 0,73]	N	0,92
Recovery	77,7 ± 68,34	114,3 ± 59,26	36,61 [-15,17 ; 88,39]	0,57 [-0,23 ; 1,34]	S	0,16

Mean Diff, Mean difference; CI, Confidence interval; ES, Effect Size; N, No effect; S, Small effect; M, Moderate effect; L, Large effect; VL, Very large effect.

Table 5.10. Between-group differences for the changes in relative oxyhaemoglobin concentration ($\Delta[O_2Hb]$) (µM) from pre- to post-testing. Results are presented as mean ± SD.

Measurement Period	Rugby	Control	Mean Diff. [95% CI]	ES [95% CI]	Qualitative Outcome	P-Value
Cognitive Testing	-22,49 ± 111,91	-2,39 ± 57,51	-20,10 [-90,43 ; 50,24]	-0,22 [-0,95 ; 0,52]	S	0,56
Recovery	-17,54 ± 103,26	36,61 ± 75,57	-51,15 [-124,63 ; 16,32]	-0,59 [-1,32 ; 0,17]	S	0,13

Mean Diff, Mean difference; CI, Confidence interval; ES, Effect Size; N, No effect; S, Small effect; M, Moderate effect; L, Large effect; VL, Very large effect.

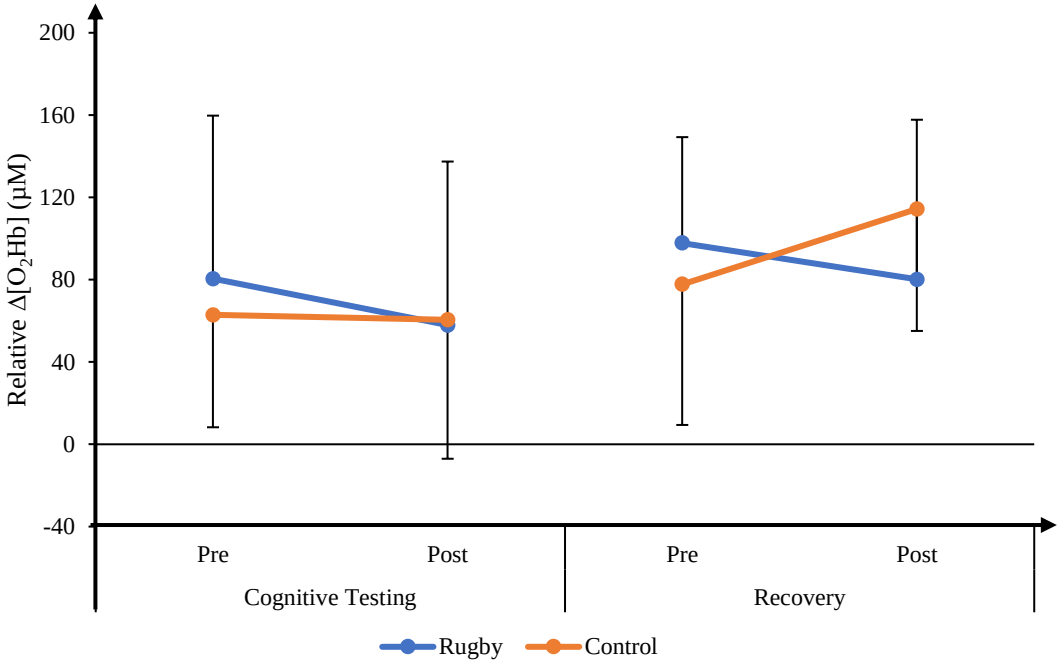


Figure 5.9. Changes in relative $\Delta[O_2Hb]$ during Cognitive Testing and Recovery from pre- to post-testing.

2. Deoxyhaemoglobin (HHb)

The global deoxyhaemoblobin concentration (Δ[HHb]) during pre- and post-testing can be seen in Figure 5.10.1 and 5.10.2. Global Δ[HHb] decreased significantly from Baseline (a) during Cognitive Testing (b2) and Recovery (c) for the Rugby group at pre-testing (exhibited by negative relative Δ[HHb] values in Fig 5.11). At post-testing, Δ[HHb] did not change significantly from Baseline for both groups during Cognitive Testing but was significantly lower than Baseline levels during Recovery for the Rugby group (P > 0,005).

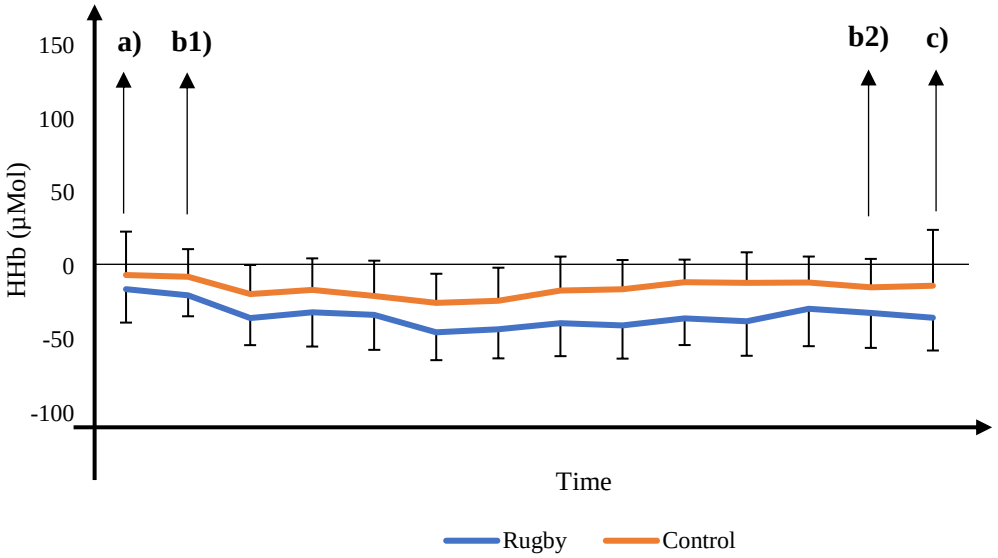


Figure 5.10.1. Global deoxyhaemoglobin concentration (Δ[HHb]) during **pre-testing** with the relevant zones, namely **a) Baseline**, **b1) Start of cognitive testing battery, b2) Cognitive Testing**, **c) Recovery**.

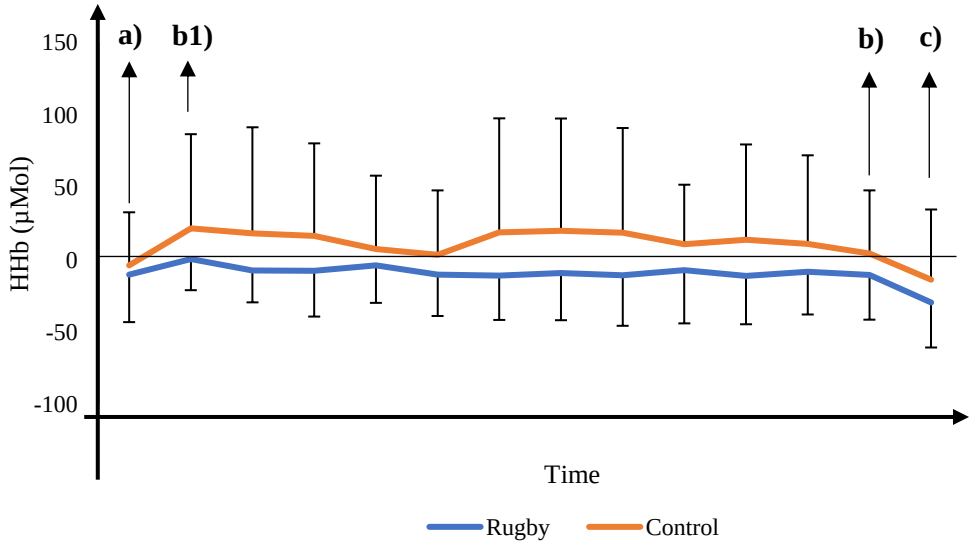


Figure 5.10.2. Global deoxyhaemoglobin concentration (Δ[HHb]) during **post-testing** with the relevant zones, namely **a) Baseline**, **b1) Start of cognitive testing battery, b2) Cognitive Testing**, **c) Recovery**.

Within-group changes in the participants' relative Δ[HHb] is summarised in Table 5.11, while between-group differences in the change of Δ[HHb] are summarised in Table 5.12. and depicted in Figure 5.11.

There were no statistically significant changes in relative Δ[HHb] from pre- to post-testing (P > 0,05). However, small to moderate practically significant increases were observed during Cognitive Testing in both the Rugby (ES = 0,57) and Control (ES = 0,71) groups respectively. The relative Δ[HHb] for both groups remained at similar levels during Recovery from pre- to post-testing.

GROUP × TIME analysis revealed that there were no statistically significant interaction effects (P > 0,05). Furthermore, it was revealed that there were no qualitative differences between the groups' mean changes from pre- to post-testing.

Table 5.11. Within-group changes in relative deoxyhaemoglobin concentration (Δ[HHb]) (µM) from pre- to post-testing. Results are presented as mean ± SD.

Rugby						
Measurement Period	**Pre**	**Post**	**Mean Diff. [95% CI]**	**ES [95% CI]**	**Qualitative Outcome**	**P-Value**
Cognitive Testing	-16,2 ± 19,20	-0,2 ± 34,85	16,00 [-4,32 ; 36,32]	0,57 [-0,15 ; 1,26]	S	0,12
Recovery	-19,5 ± 16,92	-19,1 ± 23,02	0,32 [-14,26 ; 14,91]	0,02 [-0,68 ; 0,71]	N	0,96
Control						
Measurement Period	**Pre**	**Post**	**Mean Diff. [95% CI]**	**ES [95% CI]**	**Qualitative Outcome**	**P-Value**
Cognitive Testing	-8,5 ± 27,49	8,1 ± 17,84	16,53 [-2,23 ; 35,29]	0,71 [-0,10 ; 1,48]	M	0,08
Recovery	-7,3 ± 17,64	-10,0 ± 32,44	-2,67 [-23,81 ; 18,47]	-0,10 [-0,87 ; 0,67]	N	0,80

Mean Diff. Mean difference; CI, Confidence interval; ES, Effect Size; N, No effect; S, Small effect; M, Moderate effect; L, Large effect; VL, Very large effect.

Table 5.12. Between-group differences for changes in relative deoxyhaemoglobin concentration (Δ[HHb]) (µM) from pre- to post-testing. Results are presented as mean ± SD.

Measurement Period	Rugby	Control	Mean Diff. [95% CI]	ES [95% CI]	Qualitative Outcome	P-Value
Cognitive Testing	16,00 ± 38,12	16,53 ± 28,98	-0,53 [-26,85 ; 25,79]	-0,02 [-0,75 ; 0,72]	N	0,97
Recovery	0,32 ± 28,15	-2,67 ± 24,28	2,99 [-17,31 ; 23,30]	0,11 [-0,62 ; 0,84]	N	0,76

Mean Diff. Mean difference; CI, Confidence interval; ES, Effect Size; N, No effect; S, Small effect; M, Moderate effect; L, Large effect; VL, Very large effect.

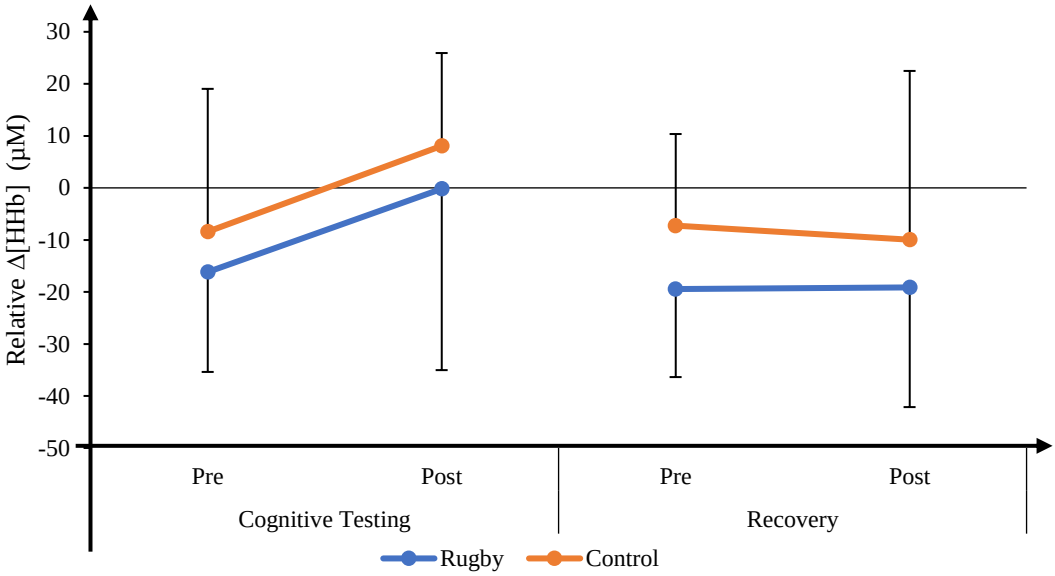


Figure 5.11. Change in relative Δ[HHb] during Cognitive Testing and Recovery from pre- to post-testing.

3. Tissue Oxygenation Index (TOI)

The global changes in tissue oxygenation index (TOI) and the relevant zones can be seen in Figure 5.12.1 and 5.12.2. Global TOI did not differ significantly from Baseline during Cognitive Testing and Recovery at pre-testing for both groups (P > 0,05). However, at post-testing it decreased significantly from Baseline for both groups during Cognitive Testing (P = 0,005 and 0,0002 for Rugby and Control respectively) but remained at similar levels during Recovery (P > 0,05).

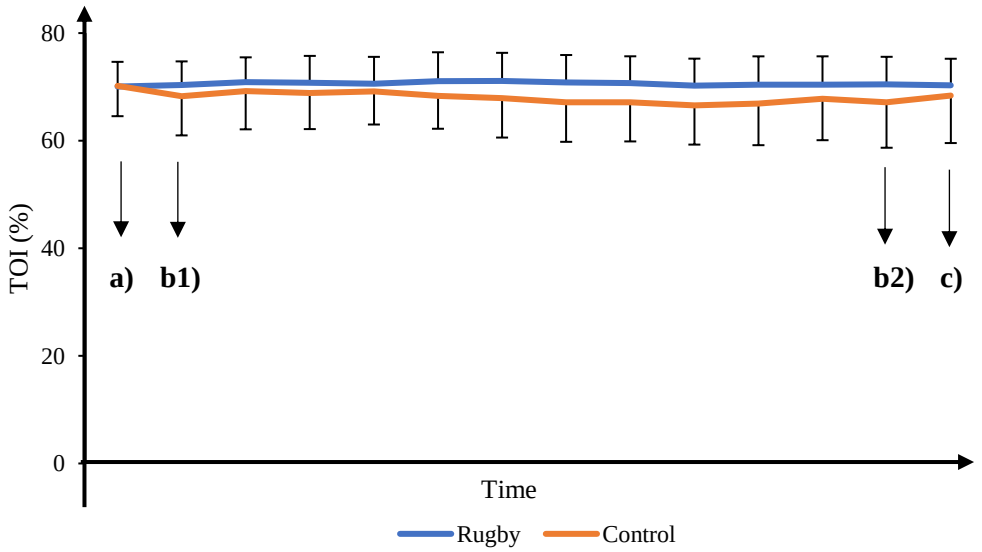


Figure 5.12.1. Global tissue oxygenation index (TOI) during **pre-testing** with the relevant zones, namely **a) Baseline**, **b1) Start of cognitive testing battery, b2) Cognitive Testing**, **c) Recovery**.

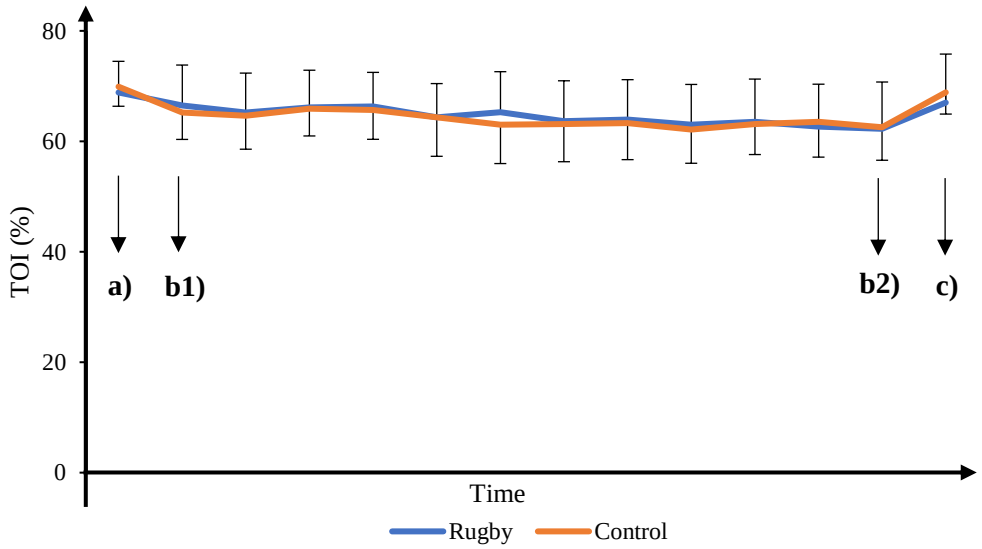


Figure 5.12.2. Global tissue oxygenation index (TOI) during **post-testing** with the relevant zones, namely **a) Baseline**, **b1) Start of cognitive testing battery, b2) Cognitive Testing**, **c) Recovery**.

Within-group changes in the participants' relative tissue oxygenation index (TOI) are summarised in Table 5.13, while between-group differences in the change of relative TOI are summarised in Table 5.14. and depicted in Figure 5.13.

The Rugby group exhibited a moderate statistically and practically significant decrease in relative TOI during Cognitive Testing (P = 0,001 ; ES = -1,19), and a small practically significant decrease during Recovery (ES = -0,42) at post-testing. There were no statistically significant changes in relative TOI for the Control group (P > 0,05), however, a moderate practically significant decrease was observed during Cognitive Testing (ES = -0,71). Additionally, a small practically significant increase in relative TOI (ES = 0,23) was observed in the Control group during Recovery.

GROUP × TIME analysis revealed that there were no statistically significant interaction effects (P > 0,05). However, a statistically significant TIME effect (P = 0,008) was found for the Rugby group, decreasing from pre- to post-testing. Comparison of the mean differences between-groups found that the Rugby group experienced a practically significant greater decline in relative TOI during Cognitive Testing (ES = -0,33) and Recovery (ES = -0,49) compared to the Control group.

Table 5.13. Within-group changes in relative tissue oxygenation index (TOI) from pre- to post-testing. Results are presented as mean ± SD.

Rugby						
Measurement Period	**Pre**	**Post**	**Mean Diff. [95% CI]**	**ES [95% CI]**	**Qualitative Outcome**	**P-Value**
Cognitive Testing	0,4 ± 2,10	-6,6 ± 8,04	-6,97 [-11,22 ; -2,73]	-1,19 [-1,90 ; -0,41]	M	0,002
Recovery	0,2 ± 2,03	-1,9 ± 6,64	-2,07 [-5,61 ; 1,48]	-0,42 [-1,11 ; 0,29]	S	0,24
Control						
Measurement Period	**Pre**	**Post**	**Mean Diff. [95% CI]**	**ES [95% CI]**	**Qualitative Outcome**	**P-Value**
Cognitive Testing	-3,0 ± 6,94	-7,3 ± 5,07	-4,31 [-9,23 ; 0,61]	-0,71 [-1,48 ; 0,10]	M	0,08
Recovery	-1,8 ± 4,36	-1,0 ± 2,09	0,79 [-1,98 ; 3,55]	0,23 [-0,55 ; 0,99]	S	0,56

Significant difference (P < 0,05). Mean Diff, Mean difference; CI, Confidence interval; ES, Effect Size; N, No effect; S, Small effect; M, Moderate effect; L, Large effect;

Table 5.14. Between-group differences for change in relative tissue oxygenation index (TOI) from pre- to post-testing. Results are presented as mean ± SD.

Measurement Period	Rugby	Control	Mean Diff. [95% CI]	ES [95% CI]	Qualitative Outcome	P-Value
Cognitive Testing	-6,97 ± 7,39	-4,31 ± 8,83	-2,67 [-8,85 ; 3,51]	-0,33 [-1,06 ; 0,42]	S	0,38
Recovery	-2,07 ± 6,30	0,79 ± 5,17	-2,85 [-7,32 ; 1,61]	-0,49 [-1,22 ; 0,27]	S	0,20

Mean Diff, Mean difference; CI, Confidence interval; ES, Effect Size; N, No effect; S, Small effect; M, Moderate effect; L, Large effect; VL, Very large effect.

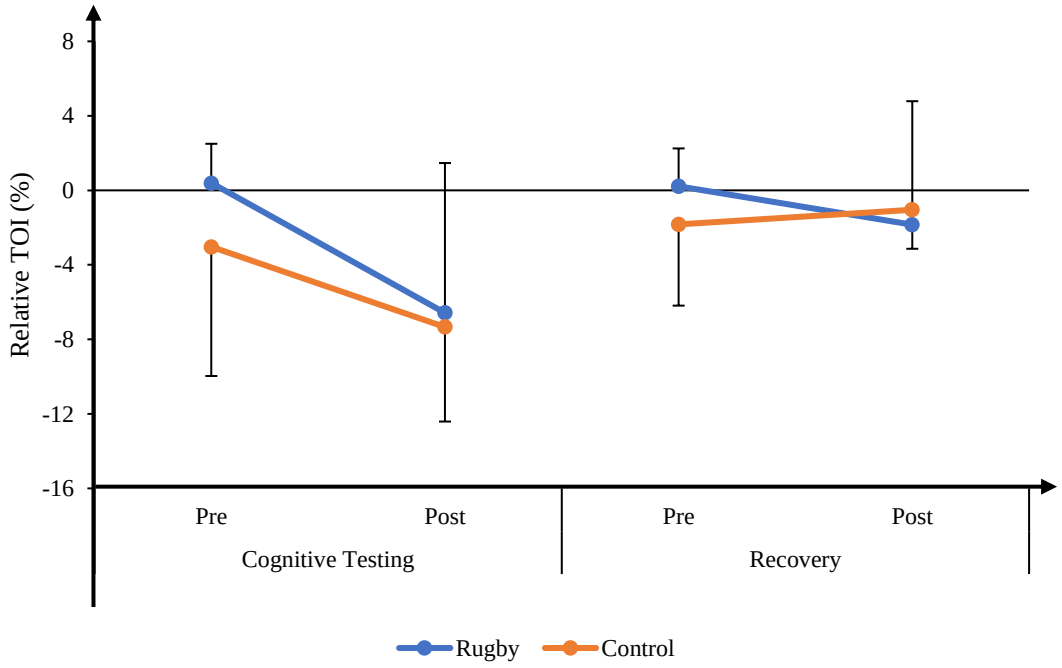


Figure 5.13. Changes in relative TOI during Cognitive Testing and Recovery from pre- to post-testing.

4. Normalised Total Haemoglobin Index (nTHI)

The global changes in normalised total haemoglobin index (nTHI) and the relevant zones during pre- and post-testing can be seen in Figure 5.14.1 and 5.14.2. Global nTHI did not change significantly over the course of measurement during pre- or post-testing in the Rugby group ($P > 0,05$). In the Control group global nTHI did not change significantly from Baseline during measurement at both pre- and post-testing.

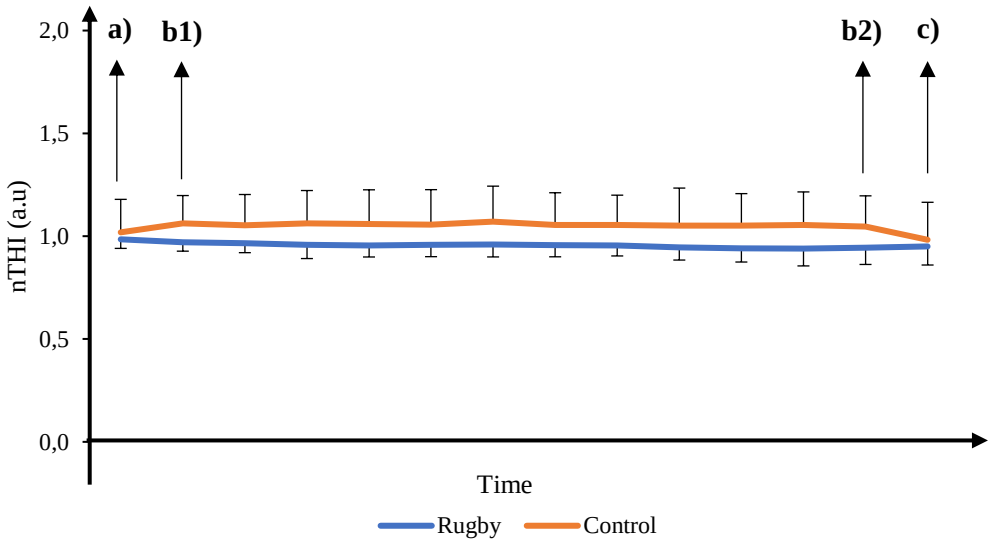


Figure 5.14.1. Global normalised total haemoglobin index (nTHI) during **pre-testing** with the relevant zones, namely **a) Baseline**, **b1) Start of cognitive testing battery, b2) Cognitive Testing**, **c) Recovery**.

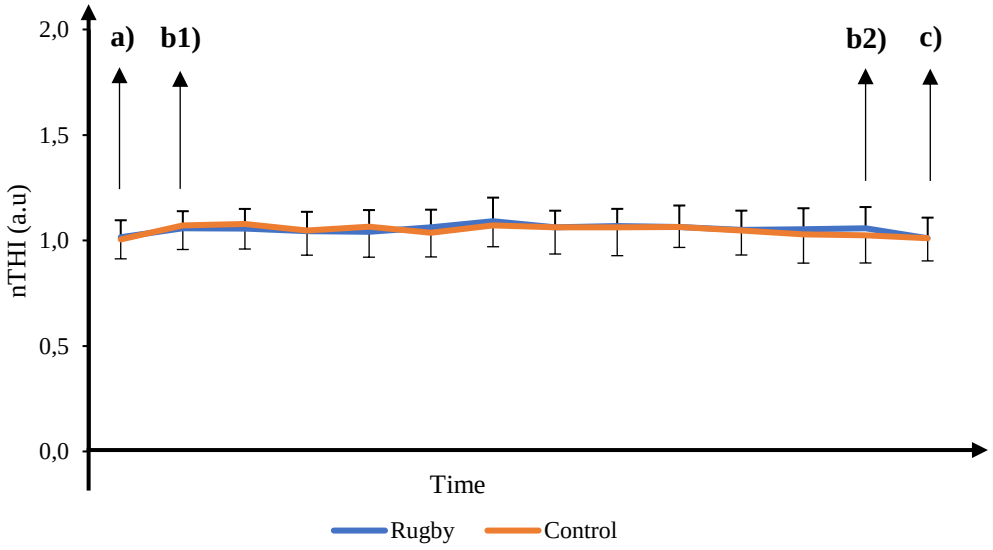


Figure 5.14.2. Global normalised total haemoglobin index (nTHI) during **post-testing** with the relevant zones, namely **a) Baseline**, **b1) Start of cognitive testing battery, b2) Cognitive Testing**, **c) Recovery**.

Within-group changes in the participants' relative normalised total haemoglobin index (nTHI) are summarised in Table 5.15, while between-group differences in the change of relative nTHI are summarised in Table 5.16. and depicted in Figure 5.15.

A statistically significant and large practically significant increase in relative nTHI was observed during Cognitive Testing (P = 0,001 ; ES = 1,29) in the Rugby group. The Rugby group also exhibited a small practically significant increase during Recovery (ES = 0,45) at post-testing. Relative nTHI remained at similar levels during Cognitive Testing in the Control group, but during Recovery there was a small practically significant increase (ES = 0,52) at post-testing.

GROUP × TIME analysis revealed that there were no statistically significant interaction effects (P > 0,05). However, the mean differences between-groups revealed that the Rugby group exhibited a moderately larger practical increase during Cognitive Testing (ES = 0,74) than the Control group at post-testing.

Table 5.15. Within-group changes in relative normalised total haemoglobin index (nTHI) from pre- to post-testing. Results are presented as mean ± SD.

Rugby						
Measurement Period	**Pre**	**Post**	**Mean Diff. [95% CI]**	**ES [95% CI]**	**Qualitative Outcome**	**P-Value**
Cognitive Testing	-0,04 ± 0,06	0,04 ± 0,07	0,08 [0,04 ; 0,13]	1,29 [0,49 ; 2,01]	L	0,001
Recovery	-0,03 ± 0,06	-0,01 ± 0,07	0,03 [-0,02 ; 0,08]	0,45 [-0,26 ; 1,14]	S	0,21
Control						
Measurement Period	**Pre**	**Post**	**Mean Diff. [95% CI]**	**ES [95% CI]**	**Qualitative Outcome**	**P-Value**
Cognitive Testing	0,03 ± 0,09	0,02 ± 0,14	-0,01 [-0,10 ; 0,09]	-0,07 [-0,83 ; 0,70]	N	0,86
Recovery	-0,04 ± 0,10	0,01 ± 0,05	0,04 [-0,02 ; 0,11]	0,52 [-0,28 ; 1,28]	M	0,20

Significant difference (P < 0,05). Mean Diff, Mean difference; CI, Confidence interval; ES, Effect Size; N, No effect; S, Small effect; M, Moderate effect; L, Large effect; VL, Very large effect.

Table 5.16. Between-group differences for change in relative normalised total haemoglobin index (nTHI) from pre- to post-testing. Results are presented as mean ± SD.

Measurement Period	**Rugby**	**Control**	**Mean Diff. [95% CI]**	**ES [95% CI]**	**Qualitative Outcome**	**P-Value**
Cognitive Testing	0,08 ± 0,10	-0,01 ± 0,15	0,09 [0,00 ; 0,19]	0,74 [-0,04 ; 1,47]	M	0,06
Recovery	0,03 ± 0,09	0,04 ± 0,11	-0,01 [-0,09 ; 0,06]	-0,13 [-0,86 ; 0,61]	N	0,73

Mean Diff, Mean difference; CI, Confidence interval; ES, Effect Size; N, No effect; S, Small effect; M, Moderate effect; L, Large effect; VL, Very large effect.

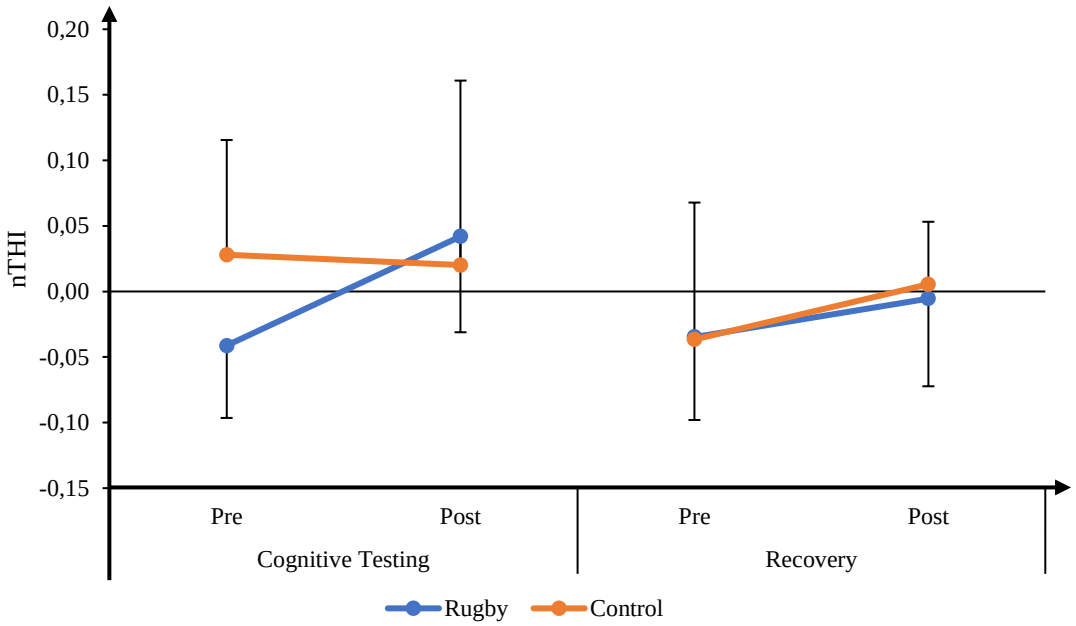


Figure 5.15. Changes in relative nTHI during Cognitive Testing and Recovery from pre- to post-testing.

F. Relationships between changes in sleep, mood state, cognitive function and cerebral oxygenation

A summary of the relationships between changes in sleep, mood state, cognitive function and cerebral oxygenation can be seen in Table 5.17. The relationship between changes cerebral oxygenation and cognitive function is depicted are Figure 5.16 – 5.19.

Small positive correlations were observed between changes in $\Delta[O_2Hb]$ and measures of mood state (r = 0,38 and 0,46 for total mood disturbance and energy index, respectively) of the Rugby group, while changes in sleep quality and $\Delta[O_2Hb]$ exhibited a moderate positive correlation (r = 0,66). The Rugby group also exhibited a small positive correlation between changes in Δ[HHb] and total mood disturbance (r = 0,33), and a moderate negative correlation between changes in TOI and sleep quantity (r = -0,67).

The Control group showed moderate positive correlations between changes in cognitive function and measures of mood state (r = 0,62 and 0,67 for total mood disturbance and energy index, respectively), and a small positive correlation between change in sleep quality and cognitive function (r = 0,30). The Control group also exhibited an additional small positive correlation between change in TOI and energy index (r = 0,30), and a small negative correlation between Δ[HHb] and sleep quantity (r = -0,41).

Regarding the relationships between cognitive testing and cerebral oxygenation it was found that the change in TOI exhibited a small negative correlation to change in neurocognitive index for the Rugby group (r = -0,32). All the relationships between the other cerebral oxygenation variables and cognitive function were found to be trivial for both groups ($-0.30 < r < 0,30$).

Table 5.17. Pearson's correlations of changes in cognitive function and cerebral oxygenation variables vs. changes sleep and mood state of the participants. Correlations are presented as r-values and 95% confidence intervals (CI).

	Rugby				
	Δ Neurocognitive Index	**Δ [O_2Hb] Test**	**Δ [HHb] Test**	**Δ TOI Test**	**Δ nTHI Test**
Sleep					
Δ Hours	0,21 [-0,32 ; 0,64]	0,04 [-0,46 ; 0,53]	0,24 [-0,29 ; 0,66]	-0,67 [-0,88 ; 0,26]**	-0,26 [-0,67 ; 0,27]
Δ Quality	0,06 [-0,45 ; 0,54]	0,66 [0,24 ; 0,87]**	-0,16 [-0,61 ; 0,36]	-0,01 [-0,50 ; 0,49]	-0,30 [-0,69 ; 0,23]*
Mood State					
Δ Total Mood Disturbance	-0,25 [-0,66 ; 0,28]	0,38 [-0,14 ; 0,74]*	0,33 [-0,20 ; 0,71]*	0,29 [-0,24 ; 0,69]	-0,19 [-0,63 ; 0,34]
Δ Energy Index	0,22 [-0,31 ; 0,65]	0,46 [-0,05 ; 0,78]*	0,04 [-0,46 ; 0,53]	0,02 [-0,48 ; 0,51]	0,07 [-0,44 ; 0,55]
	Control				
	Δ Neurocognitive Index	**Δ O_2Hb [Test]**	**Δ [HHb] Test**	**Δ TOI Test**	**Δ nTHI Test**
Sleep					
Δ Hours	-0,03 [-0,57 ; 0,53]	0,11 [-0,47 ; 0,62]	-0,41 [-0,78 ; 0,18]*	0,16 [-0,43 ; 0,65]	-0,06 [-0,59 ; 0,51]
Δ Quality	0,30 [-0,73 ; 0,30]*	-0,09 [-0,61 ; 0,49]	0,28 [-0,32 ; 0,72]	-0,03 [-0,57 ; 0,53]	0,42 [-0,17 ; 0,79]*
Mood State					
Δ Total Mood Disturbance	0,62 [0,10 ; 0,87]**	-0,13 [-0,64 ; 0,45]	-0,26 [-0,71 ; 0,34]	0,17 [-0,42 ; 0,66]	0,00 [-0,55 ; 0,55]
Δ Energy Index	0,67 [0,19 ; 0,89]**	-0,09 [-0,61 ; 0,49]	-0,18 [-0,67 ; 0,41]	0,30 [-0,73 ; 0,30]*	-0,01 [-0,56 ; 0,54]

* Small Correlation. ** Moderate Correlation. Δ Change in variable. [O_2Hb], Oxyhaemoglobin concentration; [HHb], Deoxyhaemoglobin concentration; TOI, Tissue oxygenation index; nTHI, Normalised Total Haemoglobin Index.

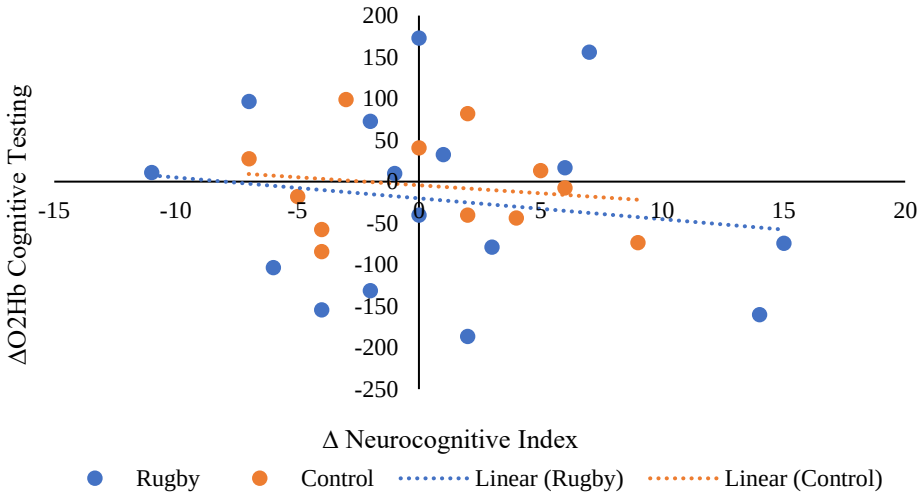


Figure 5.16. Relationship between Δ[O_2Hb] during Cognitive Testing and ΔNeurocognitive Index. Dots represent individual participant scores. Dotted lines represent line of best fit.

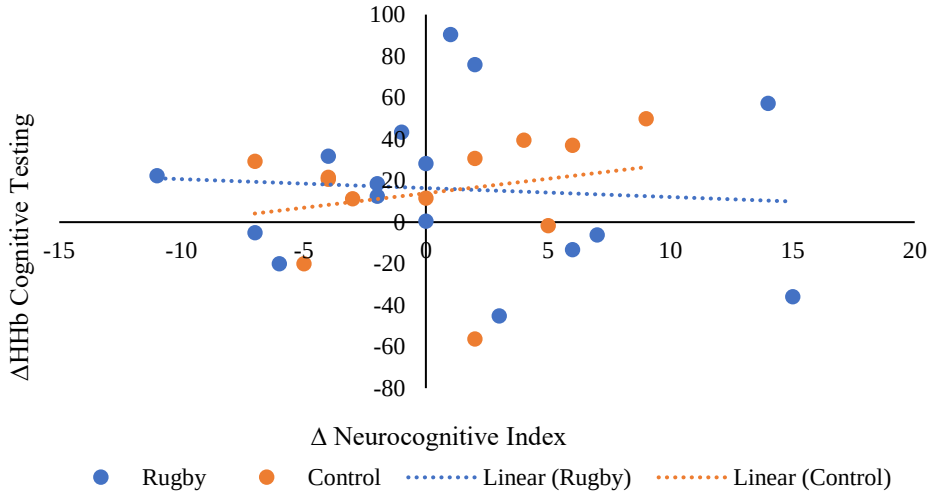


Figure 5.17. Relationship between Δ[HHb] during Cognitive Testing and ΔNeurocognitive Index. Dots represent individual participant scores. Dotted lines represent line of best fit.

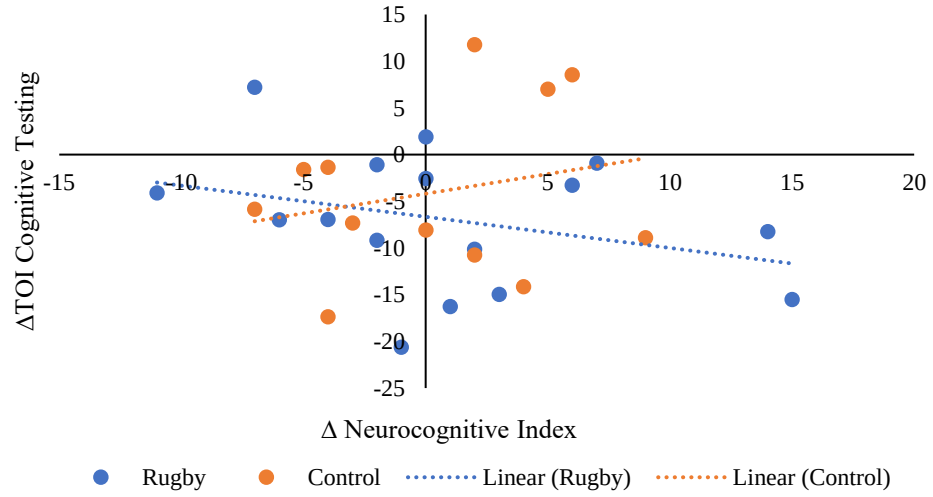


Figure 5.18. Relationship between ΔTOI during Cognitive Testing and ΔNeurocognitive Index. Dots represent individual participant scores. Dotted lines represent line of best fit.

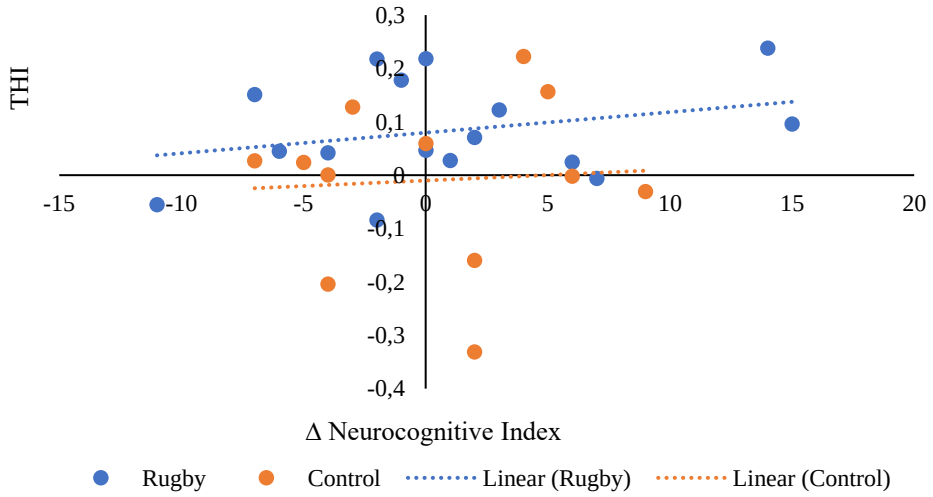


Figure 5.19. Relationship between ΔnTHI during Cognitive Testing and ΔNeurocognitive Index. Dots represent individual participant scores. Dotted lines represent line of best fit.

CHAPTER SIX

DISCUSSION

The purpose of this study was to broaden our understanding of the effects of rugby participation on the brains of players in a high-level competition. To achieve this, the changes in cognitive function and cerebral oxygenation of high-level university rugby players and non-contact sport controls were measured over the course of a fifteen-week season.

The primary finding of the study was that overall cognitive function did not change for both groups over the fifteen-week period, however, there were alterations in the cerebral haemodymics of the rugby players. Additionally, small qualitative changes were seen in a few cognitive domains of both groups. In the Rugby group, cognitive function marginally improved in areas associated with visuo-motor speed and information processing, while cerebral oxygenation consumption and blood volume during cortical activation was greatly increased. In the Control group improvements were observed in cognitive domains associated with higher thought and planning while small decrements were observed in measures of memory. However, there were no unexpected observable differences in the cerebral haemodynamics of the Control athletes.

To the author's knowledge, no other studies have examined changes in the cognitive function and cerebral haemodynamics simultaneously in rugby players over the course of a competitive tournament. This study hopes to broaden our understanding of the potential effects that rugby participation has on the brains of rugby players.

A. General Discussion

1. Participants

The Rugby and Control group did not differ significantly in age and were all currently enrolled university degree students recruited from the local university. These factors are important determinants of cognitive function and cerebral haemodynamics (Verhaeghen and Salthouse, 1997; Lee *et al.*, 2003; Reuter-Lorenz and Campbell, 2008) and have also been controlled in previous studies assessing differences between contact and non-contact sport participants (Shuttleworth-Edwards *et al.*, 2008; Bailey *et al.*, 2013; Talavage *et al.*, 2014). However, while the Rugby group was drawn from a homogenous playing field, the Control group was selected from a much more

heterogeneous sample of sports and levels of play than the rugby players. The university's 1st rugby team has a professional structure and competes amongst the top amateur teams in the nation, resulting in an intense high level of training and competition. In contrast, many of the control athletes were drawn from the 2nd or 3rd teams of their sport, thus, training and competition would have been less intense, with a lower quality of coaching staff and overall skill level of the players. Additionally, the rugby players were competing in the team's priority tournament of the season, while the control athletes participated predominantly in amateur local leagues. It is possible that these differences may have had an impact on any differences in cognitive function results observed between the groups. It has been previously shown that elite team sport athletes possess higher executive functioning and inhibitory control than athletes from a lower level of play (Kida *et* al., 2005; Huijgen *et al.*, 2015). This is thought to be due in part to the higher levels of physical training by top sportsmen that concurrently improves cognitive skills required to perform optimally in their sport. It can also be speculated that the importance of the Varsity Cup tournament to the rugby players would cause increased levels of focus and attention during training and matches that may carry over into cognitive performance.

The Rugby and Control groups were also tested in different phases of the university's academic year. The Rugby group conducted pre-testing before the commencement of university classes in January and post-testing was completed during the regular university timetable in April. The Control group conducted pre-testing later during the university's regular class timetable, either in early February or throughout March and early April. This resulted in post-testing occurring predominantly during the participants' exam schedule in late May and June. It has previously been shown that exam stress may have a beneficial effect on the executive functioning of students (Kofman *et al.*, 2006). Thus, the timing of testing and the effect of exam stress were confounding variables, which may explain some of the differences observed between the two groups. See Section A.5 for discussion of the within-group and between-group differences in cognitive function.

Mean body fat percentage between the groups did not differ significantly and all participants were categorised as "Athletic" according to the American College of Sports Medicine (ACSM) (American College of Sports Medicine, Lippincott Williams & Wilkins, 2014). The Rugby players were significantly heavier than the controls. This is likely due to a larger body stature being associated with better performance in rugby due to the collision based nature of the game (Duthie *et al.*, 2003; Sedeaud *et al.*, 2012). Furthermore, at the elite level, rugby players are typically heavier and larger than other team sport athletes, such as hockey and soccer (Duthie *et al.*, 2003). Although it has been reported that cognitive function and cerebral oxygenation may be negatively affected by high body fat percentage (Bove *et al.*, 2016; Rochette *et al.*, 2016), this factor can be disregarded in this study

since no participant was overweight or obese and there was also no difference in body composition (body fat percentage) between the groups.

2. Training data

Training of the Rugby group was monitored for a period of 15 weeks, while the average time in between testing for each player was 13,44 ± 1,02 weeks. This is shorter than the duration of other studies assessing similar changes in contact team sport athletes over the course of a season, which typically last between six months to one year or even longer (Butler *et al.*, 1993; Shuttleworth-Edwards *et al.*, 2008; Breedlove *et al.*, 2014; Talavage *et al.*, 2014; Abbas *et al.*, 2015; Helmich *et al.*, 2015; Nauman *et al.*, 2015).

Match participation for the rugby players was monitored by the researcher using video analysis. Over the course of the study the team participated in an average of 7,2 ± 2,49 matches with a mean match participation time of 7,3 ± 3,23 hours. The total number of matches and match time is not commonly reported in studies of this nature. Instead, researchers report the total number of head contacts a player suffers with the use of technology such as the Head Impact Telemetry (HIT) System that can be inserted into American Football helmets (Breedlove *et al.*, 2014; Abbas *et al.*, 2015). However, a recent study reported a mean number of 95 ± 133 subconcussive impacts per match suffered by rugby players over the course of a high level New Zealand amateur club rugby season (a playing level comparable to the participants in this study) (King *et al.*, 2014). Thus, a rough estimate for the number of subconcussive impacts suffered by players in the current study would be in the region of 684 impacts per player from match play alone. This is more than the mean number of hits experienced by high school American football players (582,8 ± 444,3 hits) in a study examining neurophysiological changes over a full season (Breedlove *et al.*, 2014). Additionally, Breedlove *et al*. (2014) stated that every player in the study that experienced more than 500 hits were flagged for impairments in either ImPACT™ test scores, fMRI scans, or both. Thus, we could consider the contact exposure within the current study's athletes as large enough to induce changes in either cognitive function or cerebral haemodynamics.

Most of the rugby team's training sessions were considered semi-contact in nature. Semi-contact sessions were defined by the researcher as sessions involving the use of tackle bags to reduce the levels of contact, or sessions where the players were instructed to make contact but at levels below that of match intensity. Even though the level of contact in these sessions is less than in contact sessions or matches, it is still likely that frequent subconcussive impacts occur. Unfortunately, data pertaining to the amount of subconcussive impacts suffered during rugby training at this level is

currently unavailable. Additionally, while the researcher personally attended all the home training sessions of the team to monitor participation, there were a number of factors that could not have been accounted for during data collection. The training squad consisted of approximately 30 – 40 players per session and was frequently split into two groups, forwards and backs, that would practice in separate areas of the stadium. Furthermore, the players were frequently swapped in and out of drills or would sit out for short periods due to minor injuries or the need to rest. Thus, it was not possible to record the exact playing time of each player per training session. Instead, total on field practice time of the team was monitored per session.

The Control group was instructed to fill in a weekly training diary and to email it to the researcher at the end of each week to ensure compliance. The Control group reported significantly less training sessions and training time than the Rugby group. This is likely due to the professional nature and set-up of the university's 1st rugby team, while the Control athletes were selected from sports with a more varied and amateur level of play. Additionally, only two athletes in the Control group reported taking a knock to the head outside of their sport that they were aware of. However, it is not possible to determine whether these could have been classified as subconcussive.

It is unknown whether the type or amount of training would have an impact on the changes in cognitive function and cerebral oxygenation of the groups. Thus, the only discriminating factor between the two groups in this study with regard training and matches, is the fact that rugby is a contact sport where it is likely that all players will be exposed to a significant number of contacts ("hits") over the course of a competition, whereas non-contact athletes would not. The results on cognitive function and cerebral haemodynamics were therefore interpreted on this premise.

3. Sleep Data

The participants' sleep quantity and quality was recorded prior to each testing session, as a lack of sleep, or restless sleep, would have influenced their performances on the cognitive function tests (Walker and Stickgold, 2004; Esposito *et al.*, 2015; Kreutzmann *et al.*, 2015; Kang *et al.*, 2016). The Rugby group did not report any change in the amount of sleep prior to the two testing sessions, however, their sleep quality was slightly better during post-testing (Pre-testing: 3,8 ± 0,54 a.u; Post-testing: 3,9 ± 0,54 a.u.; ES = 0,23). It is speculated that the players were less stressed after the conclusion of the Varsity Cup competition compared to pre-testing during the training camp. The Control group experienced a smallreduction in the amount of sleep prior to post-testing (Pre-testing: 7,7 ± 0,77 h; Post-testing: 7,2 ± 0,86 h; ES = -0,52), despite sleep quality remaining unaffected. This

is likely due to post-testing taking place during the athletes' exam period, as the participants would be more willing to sacrifice sleep in order to study for their exams.

It is possible that the changes to the sleep patterns of the participants, while not statistically significant, may have had an effect on the results. This matter is further discussed in Sections A.5. and A.6.

4. Mood State

The mood states of the participants were assessed with the Stellenbosch Mood Scale (STEMS) prior to the cognitive function tests. The degree of confusion and tension felt by the rugby players increased significantly prior to post-testing (ES = 0,67 and 0,34, respectively), however, their total mood disturbance score reflected a negligible increase (ES = 0,08). This can likely be attributed to the team's loss of the competition final prior to post-testing. In contrast, the players reported less fatigue at post-testing. This can perhaps be explained by the change in training load; pre-testing was done during the preseason training camp that involved a much higher training load when compared to peaking for the final match. The reduced fatigue levels resulted in a significantly improved energy index score for the rugby players (ES = 0,67).

The Control group also presented with slight reductions in confusion and depression (ES = -0,20 and -0,41, respectively), however, their overall mood state and energy index did not show meaningful changes (ES = 0,01 and -0,12 for total mood disturbance and energy index, respectively). From the athletes' training diaries there was no indication that these changes could be associated with any training and/or competition related factors. Furthermore, there is no objective evidence to suggest that the reduction in confusion and depression had anything to do with the exams that they were writing.

5. Cognitive Function

The CNS Vital Signs® Core testing battery (CNS Vital Signs®, 2017) consists of seven tests that contribute to 11 domains of cognitive function, and scores on each of these domains are used to calculate a composite neurocognitive index.

The first main finding is that there was no significant change in the neurocognitive index of either group at post-testing (ES = 0,11 and 0,06 for Rugby and Control, respectively). Thus, on a global level, the physical contacts experienced by rugby players did not have a detrimental effect on their cognitive function. There are a number of possible reasons why this is the case. Firstly, it is possible

that the participants' current level of play (varsity) does not produce the required frequency or intensity of contact to have a significant impact on cognitive function. Based on the findings of King *et al.* (2014) it was assumed that players at varsity level would be exposed to a significant number of contacts. However, the study lacked a direct measure for the intensity and amount of contacts suffered by each player and thus it is not possible to confirm whether contact levels fell above or below observed thresholds for subconcussive contact reported in the literature (Breedlove *et al.*, 2014).

Another reason could be the style of play utilised by the teams. Rules within the Varsity Cup competition are slightly different from the usual rules in that teams are able to score more than the standard seven points if they successfully attack and score from within their own half of play. This encourages an attacking and running brand of rugby, which was specifically evident in the Stellenbosch team who were well known for having a highly effective attacking backline. A larger focus on running rugby would typically result in less contact for the players, especially the forwards, due to less close quarters contact and set pieces throughout the game. Thus, the typical amount of subconcussive contact experienced by the players per match may have been less than that reported by King *et al*. (2014).

It is also possible that players participated in too few matches to induce substantial changes in cognitive function. The average number of matches played by each player was 7,2 ± 2,49 matches, while studies reporting observable differences in cognitive function of contact sportsmen typically included 11 or more matches over the course of their respective studies (Butler *et al.*, 1993; Shuttleworth-Edwards *et al.*, 2008; Breedlove *et al.*, 2014; Talavage *et al.*, 2014; Abbas *et al.*, 2015; Helmich *et al.*, 2015; Nauman *et al.*, 2015).

The final reason is that the combination of youth and current enrolment in an academic programme may have had a protective effect on the cognitive function of the Rugby group. Adolescence and early adulthood are associated with high levels of brain plasticity (the brain's ability to adapt to stimuli and form new synapses) (Pascual-Leone *et al.*, 2011; Giedd, 2015). The Rugby group consisted of individuals in their late teens or early twenties and thus their brains would typically have the capacity to adapt to negative stimuli in order to maintain optimal performance. In addition to this, university class participation would have acted as a positive stimulus for the cognitive function of the players. The combination of these factors may compensate for any effects induced by the level of contact experienced by the players. With a greater period of contact exposure (i.e. more matches and training) these compensatory factors may have been overwhelmed, resulting in deficits to the players' cognitive function. However, this is merely speculation at this point.

The second main finding is that the Rugby group exhibited small practically significant improvements in cognitive domains commonly associated with information processing and visuo-motor speed, but decreased slightly in the domains of simple attention and visual memory (ES = -0,26 and -0,23, respectively). The Control group showed small to moderate significant improvements in executive functioning (ES = 0,77) and cognitive flexibility (ES = 0,53), but performed worse in measures of memory.

The Rugby players improved from pre- to post-testing in the domains of cognitive flexibility (ES = 0,25), psychomotor speed (ES = 0,47) and processing speed (ES = 0,40). When compared to the Control group, a greater magnitude of improvement was still apparent for psychomotor speed (ES = 0,30) and processing speed (ES = 0,25). These "higher" level cognitive skills are associated with the ability to process information quickly and react to complex or changing external ques, employing rapid visou-motor coordination. Additionally, cognitive flexibility is assessed with tests that are commonly associated with executive functioning (i.e. the Stroop and shifting attention test), however, executive function was unchanged in the rugby players. This finding differs from studies that found impairments in these areas for American Football players, boxers and rugby players (Shuttleworth-Edwards *et al*., 2008; Bailey *et al*., 2013; Talavage *et al*., 2014; Hume *et al*., 2017).

Hume *et al*. (2017) used the same testing protocol as the current study to examine the cognitive function of retired elite and club rugby players in comparison to retired non-contact sportsmen. It was found that the rugby players performed worse in multiple cognitive domains, including cognitive flexibility and processing speed, when compared to the non-contact sport athletes. However, these participants were middle aged (43,3 ± 8,2 yrs) and had a full amateur or professional career's worth of exposure to head contact, which would typically last from childhood into the player's thirties. The current study's participants were in their early twenties (21,3 ± 1,35 yrs) with an average of two years playing experience at varsity level. Therefore, the amount and intensity of contact exposure experienced thus far by the current study's players is far less and may not be enough to induce significant deficits in cognitive function.

Huijen *et al*. (2015) provided an explanation for the improvements in the cognitive domains seen in the Rugby group. They reported that elite youth soccer players (age 13 - 17 yrs) had higher levels of cognitive flexibility and inhibitory control than sub-elite players of the same age. The authors proposed that the higher levels of training and competition experienced by elite players may actually act as "training" for these cognitive functions (Huijgen *et al*., 2015). The rugby players in the current study played in the final of the top university rugby tournament in the country and thus may be considered amongst the elite amateur players in the nation. The training and competition of the Rugby group constantly exposed the players to rapidly changing external stimuli to which they had to react

and make effective decisions, employing elite visuo-motor coordination. All the cognitive domains that saw improvement within the group rely on the ability to quickly process information and shifting stimuli, and then coordinate these visual ques into rapid motor responses. Additionally, pre-testing for the Rugby group was conducted after the players had returned from a three-week holiday that unlikely included any training that could explain improvements in information processing. Thus, it is proposed that the observed improvements in some cognitive domains may be due to a training effect resulting from high level rugby participation over the course of the study.

The Rugby group also exhibited a decrease in visual memory despite showing no changes in either verbal or composite (overall) memory. However, verbal and visual memory processing occurs predominantly in opposing hemispheres of the brain (verbal in the left medial temporal lobe (MTL) and visual in the right MTL) (Hwang and Golby, 2006; Jansen *et al.*, 2009). Thus, while the left hemisphere may have been unaffected by any subconcussive impacts, subtle alterations may have taken place within the right hemisphere that effect visual memory. Additionally, memory impairments (visuo-spatial or verbal) are one of the most commonly reported cognitive dysfunctions in contact sport literature (Killam *et al*., 2005; Bailey *et al*., 2013; Ford *et al*., 2013; Lipton *et al*., 2013; Stamm *et al*., 2015; McMillan *et al*., 2017). Thus, the small decrease in visual memory may be indicative of the beginnings of subtle impairments to the right MTL of the rugby players. However, longitudinal studies would be needed to make further inferences of this kind.

The Control group showed practically significant improvements in executive function (ES = 0,77), cognitive flexibility (ES = 0,53) and processing speed (ES = 0,21), but weaker performances in all domains of memory (ES = -0,63, -0,50 and -0,43 for composite, visual and verbal memory, respectively) and reaction time (ES = 0,27). When compared with the Rugby group the magnitude of increase for both executive function (ES = -0,67) and cognitive flexibility (ES = -0,31) was still greater for the Control group, while the decrements in memory were still evident (ES = 0,34, 0,42 and 0,12 for composite, visual and verbal memory, respectively). A possible explanation for these differences is that post-testing for the control athletes was conducted during the participants' exam time. It has been shown that the executive functioning in undergraduate university students may be improved during exams because of increased sympathetic arousal in response to moderate stress levels associated with writing exams (Kofman *et al.*, 2006). While the Control group did not report any subjective difference in stress state compared with the Rugby group, it does not exclude the possibility that they were physiologically in a state of increased sympathetic arousal resulting in improved executive functioning. However, this conclusion can only be verified with an objective measure of physiological stress, such as cortisol levels in the blood. Additionally, while the decrements in memory may appear to be in conflict with the improvements in the higher cognitive

functions, it has been shown previously that acute periods of stress may enhance memory for emotional words, but impairs memory for neutral words, which were used in the verbal memory test (Jelicic *et al.*, 2004; Smeets *et al.*, 2006). Thus, it is possible that the decreases in memory function may also be due to the timing of post-testing within the exam period.

Another explanation for the observed differences in cognitive function of the groups could be the possible effect of the qualitative changes observed in sleep patterns and mood states of the participants. While neither change in total mood disturbance or energy index showed any correlation to cognitive function in the Rugby group (r = -0,25 and 0,22, respectively), both measures of mood state were positively correlated with changes in neurocognitive index of the Control group (r = 0,62 and 0,67 for Δtotal mood disturbance and Δenergy index, respectively). Changes in sleep quantity (r = 0,21) and quality (r = 0,06) also showed only trivial correlations with changes in neurocognitive index of the rugby players, however, sleep quality (r = 0,30) was positively correlated with changes in neurocognitive index of the control athletes. Thus, while it appears unlikely that changes in these variables had an effect on the cognitive function of the rugby players, they may still have resulted in the qualitative differences observed between the groups because of its relationship with cognitive function in the control athletes.

Overall, no changes were seen in the neurocognitive index of the groups. Thus, there is no conclusive evidence that the cognitive function of the rugby players was negatively affected by contact experienced over the course of the study. However, there are a number of confounding factors that may have influenced these findings. Firstly, the Control group was tested during the exam period while the Rugby group was not. Secondly, there were differences in sleep patterns and mood state between the groups, and thirdly, stress levels were not directly measured.

6. Cerebral Oxygenation

Global changes in cerebral oxygenation variables were not reported in the results. This is because the exact path length of near-infrared light passing through biological tissue cannot be calculated, which means global changes only reflect an approximate value for each variable. Thus, relative changes from a baseline state give a more accurate indication regarding the magnitude of change in cerebral haemodynamics and cortical activation. Relative changes from Baseline for oxyhaemoglobin concentration (Δ[O_2Hb]), deoxyhaemoglobin concentration (Δ[HHb]), tissue oxygenation index (TOI) and normalised total haemoglobin index (nTHI) during Cognitive Testing and the Recovery period were calculated for all participants.

Each of the near-infrared spectroscopy (NIRS) measurements represents a different aspect of the cerebral haemodynamic response. Δ[O_2Hb] is considered a direct measure of cortical activation. This is due to an increase in regional cerebral blood flow (rCBF) via neurovascular coupling that accompanies cerebral activation (see Chapter 3) (Schroeter *et al.*, 2002; Toichi *et al.*, 2004; Sakatani *et al.*, 2006). In this study, rCBF was not measured; however, normalised total haemoglobin index (nTHI) is an indirect measure of blood flow rate. Δ[HHb] is regarded as a measure of oxygen consumption within the region, while TOI is the oxygen saturation of the vasculature.

6.1. Relative Changes During Cognitive Testing Phase

The primary focus of this section is the change in cerebral haemodynamic response during Cognitive Testing. This is due to the strong association between cerebral oxygenation and cortical activation during cognitive tasks, and the rarity of reporting cerebral haemodynamics during recovery from cognitive tasks in the literature. If subconcussive contact were to exert a negative effect on cerebral oxygenation during Cognitive Testing, we would expect a reduced relative Δ[O_2Hb], TOI and nTHI values in the rugby players at post-testing, while relative Δ[HHb] either remains unchanged or increases. In the Control group, who did not experience subconcussive contact, we would expect relative Δ[O_2Hb] and nTHI to remain the same, while relative Δ[HHb] may either decrease, increase or remain the same, and TOI may either remain the same or decrease (Meek *et al.*, 1995; Toichi *et al.*, 2004; Ehlis *et al.*, 2005; Ferreri *et al.*, 2014).

The majority of studies examining cerebral oxygenation in contact sportsmen tend to focus on changes in Δ[O_2Hb] (Damian M Bailey *et al.*, 2013; Kontos *et al.*, 2014; Helmich *et al.*, 2015). Kontos *et al*. (2014) stated that this is because changes in Δ[O_2Hb] reflect task related cortical activation better than changes in Δ[HHb]. Additionally, improved cognitive performance is typically related to an increased Δ[O_2Hb] response, thus the opposite would be true for an impairment in cognitive performance (Matsui *et al*., 2007; León-Carrion *et al*., 2008).

Kontos *et al*. (2014) used fNIRS and found a reduced Δ[O_2Hb] response in the frontal cortex of symptomatic, recently concussed university students while completing the IMPACT cognitive testing protocol, when compared to healthy controls. The authors suggested that the lowered Δ[O_2Hb] response may be due to impairments in neurometabolic function, neuronal function, neurovascular coupling, direct damage to the neurovascular system or a combination of the above (Kontos *et al.*, 2014). Helmich *et al*. (2015) found similar impairments in the Δ[O_2Hb] response of university sport students with persistent post-concussive symptoms (mean of 21 ± 21 months post-concussion). These researchers also reported a correlation between the severity of post-concussive symptoms and the

decrease in Δ[O_2Hb] in the left prefrontal cortex (LPFC) (Helmich *et al.*, 2015). Unfortunately, these studies did not report on nTHI or other measures of blood flow rate, though as Δ[O_2Hb] is typically linked with nTHI it is likely that blood flow rate saw a similar decrease.

Bailey *et al*. (2013) found that cerebral haemodynamics and cognitive function was chronically impaired in professional boxers with a mean career length of 13 ± 4 years (includes amateur and professional career). The authors utilised multiple methods to analyse various aspects, such as cerebral oxygenation and cerebrovascular autoregulation (control of blood flow to the brain), and found that the boxers with the most marked cerebral haemodynamic impairments had the highest sparring volume scores over their careers (Bailey *et al.*, 2013). Studies on high school American football players found reduced cerebral activation levels and impaired cerebrovascular reactivity to CO_2 (CVR_{CO2}) over the course of a season (± one year) when compared to preseason baselines levels (Talavage *et al.*, 2014; Shenk *et al.*, 2015; Svaldi *et al.*, 2015). CVR_{CO2} is the ability of the cerebral blood vessels to dilate in response to CO_2 and is thus a measure of local blood flow and volume, similar to nTHI (Svaldi *et al.*, 2015).

While Δ[HHb] is not commonly reported in contact sport literature, other studies reported that Δ[HHb] levels typically decrease from baseline values during cortical activation (Schroeter *et al.*, 2002, 2004; Franceschini *et al.*, 2003; Toichi *et al.*, 2004; Sakatani *et al.*, 2006; Matsui *et al.*, 2007; León-Carrion *et al.*, 2008; Ferreri *et al.*, 2014). In contrast, some studies reported no change in Δ[HHb] concentration, or even an increase (Meek *et al.*, 1995; Toichi *et al.*, 2004; Ehlis *et al.*, 2005; Ferreri *et al.*, 2014). Higher concentrations of Δ[HHb] are thought to indicate greater oxygen utilization by the neurons, which infers a greater neural effort is required to complete the set task (Murata *et al.*, 2002). As mentioned earlier, if contact experienced by the players inflicted microtraumas throughout the brain, it would cause damage to either the neurovascular network, the neurocoupling system, or the neurons themselves. If the neurovascular network or neurocoupling system were to be impaired, blood flow through the brain would be reduced. This would result in greater O_2 extraction and utilisation by the neurons and reduced HHb clearance from the area, leading to higher relative Δ[HHb] values (Toichi *et al.*, 2004; Murata *et al.*, 2006). If the neurons themselves have suffered trauma, neural efficiency could be reduced, either within the region or elsewhere within the neural network (Murata *et al.*, 2002, 2006). This would result in an upregulation of cellular metabolism in order to maintain optimal function (Murata *et al.*, 2002, 2006; Sloubanov *et al.*, 2017). This would in-turn lead to greater oxygen utilisation and thus higher HHb levels.

TOI is not commonly reported in the literature. However, as it is a measure of oxygen saturation we can deduce that a decrease in Δ[O_2Hb] combined with an increase in Δ[HHb] would lead to lower TOI values. Due to its rarity in the literature, TOI will not be discussed beyond reporting of the result.

The results of the study revealed that within the Rugby group relative values decreased for Δ[O_2Hb] (ES = -0,28) and TOI (ES = -1,19) during Cognitive Testing at post-testing, and increased for HHb (ES = 0,57). However a significant increase in relative nTHI (P = 0,01 ; ES = 1,29) was observed in addition to the increase in Δ[HHb] of the group. In the Control group relative Δ[O_2Hb] (ES = -0,04) and nTHI remained the same, TOI decreased (ES = -0,71), and Δ[HHb] increased (ES = 0,71). Additionally, when the change in relative NIRS measurements was compared between groups it was revealed that the Rugby group experienced a larger magnitude of decrease in relative Δ[O_2Hb] (ES = -0,22) and TOI (ES = -0,33) than the Control group, and a larger increase in nTHI (ES = 0,74). The magnitude of increase in relative Δ[HHb] was the same for both groups (ES = -0,02). Thus, the observed cerebral oxygenation response during Cognitive Testing at post-testing of the Control group concurred with the expected response. However, in the Rugby group there were differences from the expected response. The expected and observed cerebral oxygenation responses for both groups during Cognitive Testing are depicted in Figure 6.1.

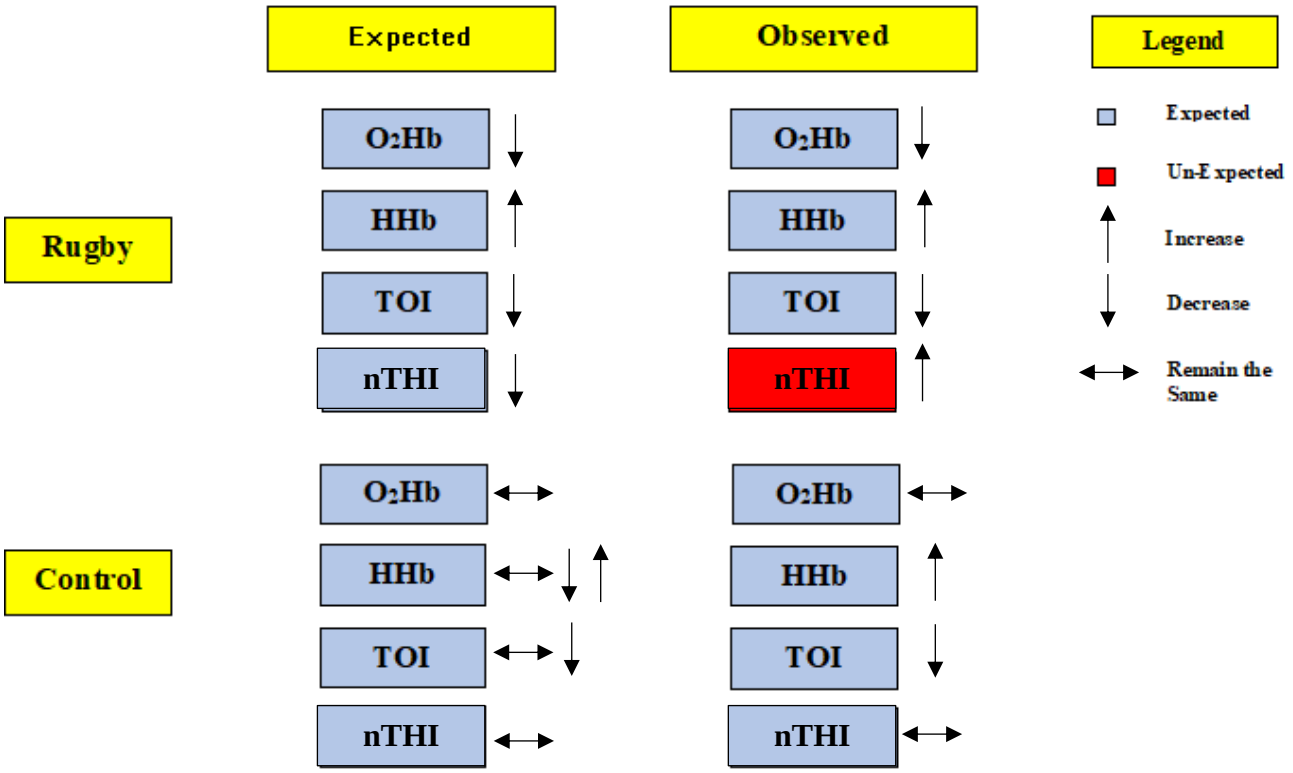


Figure 6.1. Expected *versus* observed changes in oxyhaemoglobin (Δ[O_2Hb]), deoxyhaemoglobin (Δ[HHb]), tissue oxygenation index (TOI) and normalised total haemoglobin index (nTHI) for Rugby and Control.

In the Rugby group changes in relative Δ[O_2Hb], Δ[HHb] and TOI matched the response that would be expected from individuals who have undergone substantial amounts of repetitive head contact. However, relative nTHI exhibited an unexpected change, namely a significant increase (P = 0,001; ES = 1,29) as opposed to the expected decrease. This may be considered an unusual finding as

typically when a decrease in Δ[O_2Hb] is observed there is an accompanying decrease in nTHI. An increase in relative nTHI and Δ[HHb] accompanied by a decrease in Δ[O_2Hb] indicates that oxygen utilisation increased to a larger extent than regional cerebral blood volume, i.e. oxygen demand was greater than the increase in oxygen supply. This pattern has been observed previously in the contralesional (unaffected) cerebral hemisphere of recovering stroke patients (Murata *et al.*, 2002, 2006). It was thought that this is a compensatory response and that increased load is placed on the healthy neurons to maintain cognitive performance, despite damage to other regions of the neural network (Murata *et al.*, 2002, 2006). Sloubanov *et al.* (2017) echoed this theory when they observed increased cerebral blood volume in college football players. The authors also stated that this was likely a compensatory response for decreased inefficiency throughout the brain. While extreme degrees of brain damage were not present in the current study's participants, it is possible that the repetitive contact suffered by the rugby players has resulted in subtle deficits throughout their neural network. This would in turn place a greater load on the prefrontal cortex during cortical activation as this is the primary cortical area involved in executive or 'higher' cognitive processes. Thus, it is possible that the observed decrease in relative Δ[O_2Hb] accompanied by increases in relative Δ[HHb] and nTHI of the rugby players may be the result of increased load being placed on the prefrontal cortex due to impairments elsewhere in the brain. As previously discussed, these impairments could be structural, functional or metabolic in nature, however, further research examining multiple cortical regions is needed to further add to this argument.

The results revealed that changes in the relative NIRS measures of the Control group were as expected. Both relative Δ[O_2Hb] and nTHI remained at similar levels during the pre- and post-testing periods. This makes sense as overall cognitive function did not change within the group, and none of the athletes experienced substantial repetitive head contact during the study as in the Rugby group. Relative Δ[HHb] showed a moderate practically significant increase from Baseline for the group (ES = 0,71). As mentioned earlier this indicates higher oxygen utilisation during the cortical tasks. The reason for this is unknown, however, increased Δ[HHb] concentrations from baseline measurements is a common finding in healthy individuals throughout literature (Meek *et al.*, 1995; Toichi *et al.*, 2004; Ehlis *et al.*, 2005; Ferreri *et al.*, 2014).

There are a number of other factors that may have had an effect on the cerebral oxygenation measurements of the groups. The participants' mood state and sleep patterns have the potential to effect cerebral haemodynamics via increased cortisol levels associated with increased stress and reduced sleep quantity and quality. Unfortunately, cortisol levels were not measured in the current study, however, sleep patterns and mood states were. Sleep quality and energy index of the Rugby players saw small to moderate increases at post-testing and changes in both these variables were

positively correlated with changes in relative Δ[O_2Hb] of the group (r = 0,66 and 0,46 for sleep quality and energy index, respectively). This indicates that players who obtained higher quality sleep and felt more energetic had higher levels of cerebral oxygenation. However, none of the group's other NIRS variables or neurocognitive index showed any correlation, suggesting that this is unlikely. In the Control group, only sleep quantity showed any change, decreasing from the pre-testing period. Changes in sleep quantity showed a negative correlation with changes in relative Δ[HHb] (r = -0,41). Thus, Control athletes who obtained less sleep may have experienced greater oxygen utilisation during testing. Other factors that have been shown to affect cerebral oxygenation readings are fitness levels and skin temperature. Unfortunately, these factors were not measured in this study.

6.2. Relative changes during the Recovery Phase

The author is unaware of other studies reporting on the recovery of cerebral haemodynamics upon the completion of a cognitive task. Thus, the discussion will be focused on what the relative cerebral haemodynamics during Recovery infer and what changes in these variables may imply based on contact sport literature.

It was found that Δ[O_2Hb] increased further during Recovery from the Cognitive Testing phase for both groups during the pre- and post-testing interval. This infers that oxygen utilisation of the neurons decreased upon cessation of cortical activity, while rCBF was maintained for a short period of time (similar to the recovery of heart rate at the cessation of exercise). Indeed, relative Δ[HHb] values were below Baseline values at both testing periods for both groups, indicating that oxygen utilisation was reduced during this time. Additionally, relative nTHI was similar to Cognitive Testing values for the Rugby group during recovery, while in the Control nTHI it did not differ from Baseline during pre- and post-testing. Thus, it can be deduced that the typical haemodynamic response of the groups during Recovery was for oxygen utilisation to decrease, while blood flow was maintained for a short period of time.

Both groups experienced changes in their relative cerebral haemodynamics during the Recovery phase at post-testing. Relative Δ[O_2Hb] increased in the Control group (ES = 0,57). This is likely due to an increase in cerebral blood flow, as indicated by a greater relative nTHI (ES = 0,52). As relative Δ[HHb] did not change (ES = -0,10) it can be inferred that the blood flow increased while oxygen utilisation remained the same which resulted in higher concentrations of O_2Hb. The reason for this increase in blood flow is not apparent. It is possible that sympathetic activity was increased in the Control athletes, potentially as the result of exam stress, which would have resulted in increased cortisol levels and leading to a greater distribution of blood flow to the brain. However, relative nTHI did not change during Cognitive Testing, which does not fit this explanation.

In the rugby players, it is not apparent why relative Δ[O_2Hb] decreased (ES = -0,27), with a simultaneous increase in relative nTHI (ES = 0,45), while Δ[HHb] remains the same (ES = 0,02). It could be speculated that oxygen utilisation by the neurons was still higher during Recovery at post-testing, but that the increase in blood flow (nTHI) resulted in clearance of the excess HHb from the vasculature. This would indicate that neural efficiency has been impaired leading to an upregulation of cellular metabolism as explained in Section A.6.1. However, this is merely speculation and further research into the cerebral haemodynamics after exposure to cognitive stress is needed in both sedentary individuals and contact sport athletes. Additionally, the same factors that may have affected measurements during cognitive testing may also have affected the readings during Recovery.

B. Summary

To date no other studies have examined the changes in cognitive function and cerebral oxygenation of rugby players with the simultaneous use of cognitive tests and near-infrared spectroscopy (NIRS). The focus of research, especially in a South African context, has been on the identification of concussion and its acute effects on players. Little attention is directed at the possible long-term effects of repetitive head trauma associated with the game, especially in young players, despite a growing body of evidence suggesting that contact sport participation is linked to cognitive deficits and neurodegeneration later in life.

It was hypothesized at the beginning of this study, that cerebral oxygenation responses will be reduced in the rugby players after 15 weeks of exposure to rugby contact, and that this reduced response will be accompanied by decreased cognitive performance. In addition, it was hypothesized that changes may be observed in sleep patterns and mood states at the end of the competitive season would not have an effect on cognitive function and cerebral oxygenation, neither in rugby players, nor non-contact sport athletes.

The results revealed that overall cognitive function did not change for either group over the duration of the study. However, certain aspects of cognitive function were significantly altered in both groups. It was speculated that these differences were the result of the high-quality practice and competition the rugby players experienced over the course of the study, and that the Control athletes were tested during their exam period while the Rugby players were not. Additionally, there were changes in sleep and mood pattern that may have affected the results, as evident from its influence on the cognitive function in the Control group.

It was revealed that the Rugby group exhibited reduced cerebral oxygenation concentration at post-testing, but increased in measures of oxygen consumption and cerebral blood flow rate in comparison

to the Control group. This may indicate that subtle impairments have occurred in the brains of the rugby players that resulted in reduced neuronal efficiency. This then places a greater load on the prefrontal cortex to maintain cognitive performance. While it is not certain that these changes are the result of the contact suffered by the participants, it is worrying that unusual changes have taken place in the cerebral haemodynamics of the players over the short-time frame of the study. As with cognitive function, it is possible that changes in the mood state and sleep patterns of the participants may have had small qualitative effects on measures of cerebral haemodynamics.

In conclusion, overall cognitive performance was not affected by a 15-week varsity rugby season, however, the cerebral haemodynamics of the rugby players was altered at the post-testing interval. This indicates that while the players' cognitive performance was maintained, subtle impairments throughout their brains may have occurred as a result of participation in their sport. Thus, although a 15-week season may not have been enough to induce obvious negative changes in rugby players' cognitive function, exposure to contact over the course of multiple seasons may cause neural impairments to the extent that cognitive function, and health, are affected later in life. Until large-scale, longitudinal studies are conducted that examine multiple brain regions of rugby players, these theories will remain mere speculation.

C. Limitations of the Study

A limitation of the study was the small sample size in the Rugby and Control groups. Despite the Rugby group all being of a similar age and education status there is large interpersonal variability in the structure and function of peoples' brains and how it reacts to trauma. A large sample size would minimize these effects and infer more confidence in the results. Additionally, the Control group was drawn from a variety of sports and thus lacked homogeneity. This should be controlled for in future studies.

Additionally, a number of participants in the study were of either of mixed race or African ethnicity. Darker skin pigmentations have been previously shown to affect NIRS readings.

Another limiting factor is that education status was not directly controlled for. Although all the participants were registered university students at the time of the study, they studied a wide variety of degrees and were at different stages in their tertiary education.

Chronic and physiological stress measures were not implemented in the study. Cortisol analysis would have allowed for more definitive deductions regarding the participants' acute and chronic stress states. Additionally, there was a lack of a reliable measure of sleep quantity and quality.

Another limitation is that concussions frequently go undiagnosed within the contact sport arena. Thus, there was no way of knowing for certain that none of the participants suffered a concussion over the course of the study that would have affected their results. Additionally, it was not possible to calculate the exact amount of subconcussive contact suffered by each player during rugby participation, as well as outside of the sport. Training and match-play time were used as a rough estimate for contact exposure based on findings by King *et al*. (2014), who assessed subconcussion incidence during rugby match-play.

Participant accuracy and compliance in completing relevant training diaries and noting potential subconcussive knocks may be considered as an additional limiting factor. What may be considered a relevant bump to the head is a subjective observation, and thus some Control participants may have failed to note subconcussive contact experienced over the course of the study.

A further limitation was that changes in fitness levels of the participants could not be measured over the course of the study. This was due to the availability of the participants' and the nature of their training schedule. It is recognised that changes in fitness level, especially improvements, may account for some of the changes that were observed in cognitive performance and cerebral haemodynamics.

Another limitation is the possibility of human error regarding placement of the NIRS probes and operation of the NIRO200-NX Oxiometer. Although every effort was made to execute placement according to the international 10-20 classification system and the researcher was educated in the operation of the device, small deviations in the placement from pre- to post-testing may have occurred.

A further confounding factor is the interpersonal variability in skull thickness and vasculature of the skin. These were factors that could not be controlled for and may have small effects on cerebral oxygenation readings. Additionally, skin temperature data was unavailable over the course of the study.

Another limiting factor was that the NIRO200-NX Oxiometer could only measure haemodynamic changes within the prefrontal cortex, with a maximum of two channels. Thus, it is not known if any changes took place in the oxygenation of other regions within the brain. Additionally, cerebral blood flow was not directly measured with the use of a reliable technique such as transcranial Doppler analysis.

D. Recommendations for Future Studies

Future studies should examine the changes in cognitive function of rugby players over multiple seasons, so that we can better understand the effects of a career's worth of rugby may have on a player. Studies should also make use of more homogenous control groups to better control for playing level and training time. Researchers should also consider monitoring cortisol levels of players as this provides a more accurate indication of chronic stress state. Studies should also make use of more reliable measures of sleep quantity and quality, such as the Pittsburgh Sleep Quality Index. Fitness levels of the participants should be measured to control for the influence that aerobic fitness has on cognitive function and the brain. Additionally, multiple regions of the brain should be studied during cortical activation to further explore the arguments of the current study. Finally, future studies should also compare forward and backline players, as the forwards tend to experience a higher frequency of contact while the backline players make contact at higher velocities.

REFERENCES

Abbas, K., Shenk, T. E., Poole, V. N., Breedlove, E. L., Leverenz, L. J., Nauman, E. A., Talavage, T. M. and Robinson, M. E. (2015). Alteration of default mode network in high school football athletes due to repetitive subconcussive mild traumatic brain injury: a resting-state functional magnetic resonance imaging study. *Brain Connectivity*, 5(2): 91–101.

Abler, B., Roebroeck, A., Goebel, R., Höse, A., Schönfeldt-Lecuona, C., Hole, G. and Walter, H. (2006). Investigating directed influences between activated brain areas in a motor-response task using fMRI. *Magnetic Resonance Imaging*, 24(2): 181–185.

Alvarez, J. A. and Emory, E. (2006). Executive function and the frontal lobes: A meta-analytic review. *Neuropsychology Review*, 16(1): 17–42.

American College of Sports Medicine. (2014). *ACSM's Guidelines for Exercise Testing and Prescription*. 9th Edition. Philadelphia, PA: Lippincott Williams & Wilkins.

Bailey, D. M., Jones, D. W., Sinnott, A., Brugniaux, J. V, New, K. J., Hodson, D., Marley, C. J., Smirl, J. D., Ogoh, S. and Ainslie: N. (2013). Impaired cerebral haemodynamic function associated with chronic traumatic brain injury in professional boxers. *Clinical Science*, 124(3): 177–189.

Baker, J. F., Devitt, B. M., Green, J. and McCarthy, C. (2013). Concussion among under 20 rugby union players in Ireland: Incidence, attitudes and knowledge. *Irish Journal of Medical Science*, 182(1): 121–125.

Barkhoudarian, G., Hovda, D. A. and Giza, C. C. (2011). The molecular pathophysiology of concussive brain injury. *Clinics in Sports Medicine*, 30(1): 33–48.

Baugh, C. M., Stamm, J. M., Riley, D. O., Gavett, B. E., Shenton, M. E., Lin, A., Nowinski, C. J., Cantu, R. C., McKee, A. C. and Stern, R. A. (2012). Chronic traumatic encephalopathy: Neurodegeneration following repetitive concussive and subconcussive brain trauma. *Brain Imaging and Behavior*, 6(2): 244–254.

Belanger, H. G., Vanderploeg, R. D., Curtiss, G. and Warden, D. L. (2007). Recent neuroimaging techniques in mild traumatic brain injury. *Journal of Psychiatry and Clinical Neuroscience*, 19(1): 5–20.

Belanger, H. G., Vanderploeg, R. D. and McAllister, T. (2015). Subconcussive blows to the head. *Journal of Head Trauma Rehabilitation*, 31(3): 159-166.

Benson, B. W., Mohtadi, N. G., Rose, M. S. and Meeuwisse, W. H. (1999). Head and neck injuries among ice hockey players wearing full face shields vs half face shields. *JAMA: Journal of the American Medical Association*, 282(24): 2328–2332.

Boersma, H. and Das, J. P. (2008). Attention, attention rating and cognitive assessment: A review and a study. *Developmental Disabilities Bulletin*, 36(1/2): 1–17.

Borrenson, J. and Lambert, M. (2006). Validity of self-reported training duration. *International Journal of Sport Science and Coaching*, 1(4): 353–359.

Bove, R. M., Gerweck, A. V., Mancuso, S. M., Bredella, M. A., Sherman, J. C. and Miller, K. K. (2016). Association between adiposity and cognitive function in young men: Hormonal mechanisms. *Obesity*, 24(4): 954–961.

Breedlove, E. L., Robinson, M., Talavage, T. M., Morigaki, K. E., Yoruk, U., O'Keefe, K., King, J., Leverenz, L. J., Gilger, J. W. and Nauman, E. A. (2012). Biomechanical correlates of symptomatic and asymptomatic neurophysiological impairment in high school football. *Journal of Biomechanics*, 45(7): 1265–1272.

Breedlove, K. M., Breedlove, E. L., Robinson, M., Poole, V. N., King, J. R., Rosenberger, P., Rasmussen, M., Talavage, T. M., Leverenz, L. J. and Nauman, E. A. (2014). Detecting neurocognitive and neurophysiological changes as a result of subconcussive blows in high school football athletes. *Athletic Training & Sports Health Care*, 6(3): 119–128.

Butler, R. J., Forsythe, W. I., Beverly, D. W. and Adams, L. M. (1993). A prospective controlled investigation of the cognitive effects of amateur boxing. *Journal of Neurology, Neurosurgery, and Psychiatry*, 56(10): 1055–61.

Butts, K. A., Floresco, S. B. and Phillips, A. G. (2013). Acute stress impairs set-shifting but not reversal learning. *Behavioural Brain Research*, 252(1): 222–229.

Camfield, D. A., Stough, C., Farrimond, J. and Scholey, A. B. (2014). Acute effects of tea constituents L-theanine, caffeine, and epigallocatechin gallate on cognitive function and mood: A systematic review and meta-analysis. *Nutrition Reviews*, 72(8): 507–522.

Carpenter, P. A., Just, M. A. and Reichle, E. D. (2000). Working memory and executive function: evidence from neuroimaging. *Current Opinion in Neurobiology*, 10(2): 195–199.

Casson, I. R., Viano, D. C., Haacke, E. M., Kou, Z. and LeStrange, D. G. (2014). Is there chronic brain damage in retired NFL players? neuroradiology, neuropsychology, and neurology examinations of 45 retired players. *Sports Health*, 6(5): 384–395.

Chang, Y. K., Chu, C. H., Wang, C. C., Wang, Y. C., Song, T. F., Tsai, C. L. and Etnier, J. L. (2015). Dose-response relation between exercise duration and cognition. *Medicine and Science in Sports and Exercise*, 47(1): 159–165.

Chong, C. S. (2008). Management strategies for post-concussion syndrome after mild head injury: A systematic review. *Hong Kong Journal of Occupational Therapy*. Elsevier, 18(2): 59–67.

Clarys, J. P., Provyn, S., Marfell-Jones, M. and Van Roy, P. (2006). Morphological and constitutional comparison of age-matched in-vivo and post-mortem populations. *Morphologie*, 90(291): 189–196.

Clay, M. B., Glover, K. L. and Lowe, D. T. (2013). Epidemiology of concussion in sport: A literature review. *Journal of Chiropractic Medicine*, 12(4): 230–251.

CNS Vital Signs®, (2017). *CNS Vital Signs Interpretation Guide*.

Coetsee, C. and Terblanche, E. (2017). Cerebral oxygenation during cortical activation: The differential influence of three exercise training modalities. A randomized controlled trial. *European Journal of Applied Physiology*, 117(8): 1617–1627.

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

Coughlan, G. F., Green, B. S., Pook: T., Toolan, E. and O'Connor, S. P. (2011). Physical game demands in elite Rugby Union: a global positioning system analysis and possible implications for rehabilitation. *The Journal of Orthopaedic and Sports Physical Therapy*, 41(8): 600–605.

Davis, S. L. (2006). Skin blood flow influences near-infrared spectroscopy derived measurements of tissue oxygenation during heat stress. *Journal of Applied Physiology*, 100(1): 221–224.

Dean: J. A. and Sterr, A. (2013). Long-term effects of mild traumatic brain injury on cognitive performance. *Frontiers in Human Neuroscience*, 7: 1–11.

Dehghani, H. and Delpy, D. T. (2000). Near-infrared spectroscopy of the adult head: Effect of scattering and absorbing obstructions in the cerebrospinal fluid layer on light distribution in the tissue. *Applied Optics*, 39(25): 4721–4729.

Dessy, A. M., Rasouli, J. and Choudhri, T. F. (2014). Second impact syndrome: A rare, devastating consequence of repetitive head injuries. *Neurosurgery Quarterly*, 10(3): 423–426.

Diamond, A. (2013). Executive Functions. *Annual Review of Psychology*, 64(1): 135–168.

Di Virgilio, T. G., Hunter, A., Wilson, L., Stewart, W., Goodall, S., Howatson, G., Donaldson, D. I. and Ietswaart, M. (2016). Evidence for acute electrophysiological and cognitive changes following routine soccer heading. *EBioMedicine*, 13: 66–71.

Dupuy, O., Gauthier, C. J., Fraser, S. A., Desjardins-Crèpeau, L., Desjardins, M., Mekary, S., Lesage, F., Hoge, R. D., Pouliot, P. and Bherer, L. (2015). Higher levels of cardiovascular fitness are associated with better executive function and prefrontal oxygenation in younger and older women. *Frontiers in Human Neuroscience*, 9: 1–12.

Ehlis, A. C., Herrmann, M. J., Wagener, A. and Fallgatter, A. J. (2005). Multi-channel near-infrared spectroscopy detects specific inferior-frontal activation during incongruent Stroop trials. *Biological Psychology*, 69(3): 315–331.

Ehlis, A., Schneider, S., Dresler, T. and Fallgatter, A. J. (2014). Application of functional near-infrared spectroscopy in psychiatry. *NeuroImage*, 85(1): 478–488.

Ellis, M. J., Leddy, J. and Willer, B. (2016). Multi-disciplinary management of athletes with post-concussion syndrome: An evolving pathophysiological approach. *Frontiers in Neurology*, 7(136): 1–14.

Esposito, M. J., Occhionero, M. and Cicogna, P. (2015). Sleep deprivation and time-based prospective memory. *Sleep*, 38(11): 1823–1826.

Faden, A. I. and Loane, D. J. (2015).Chronic neurodegeneration after traumatic brain injury: Alzheimer disease, chronic traumatic encephalopathy, or persistent neuroinflammation? *Neurotherapeutics*, 12(1): 143–150.

Fantini, S., Hueber, D., Angela, M., Kohl, M., Nolte, C., Heekeren, H. R., Duncan, A., Meek, J. H., Clemence, M., Klassen, L. M., Macintosh, B. J., Menon, R. S., Hebden, J. C., Gibson, A. and Yusof, R. (1996). The effect of scalp ischaemia on measurement of cerebral blood volume by near-infrared spectroscopy pulse signals using phase resolved optical spectroscopy The effect of scalp ischaemia on measurement of cerebral blood volume by near-infrared spectroscopy. *Physiological Measurement*, 17(4): 279–287.

Ferrari, M., Mottola, L. and Quaresima, V. (2004). Principles, techniques, and limitations of near infrared spectroscopy. *Canadian Journal of Applied Physiology*, 29(4): 463–87.

Ferrari, M. and Quaresima, V. (2012). Near infrared brain and muscle oximetry: From the discovery to current applications. *Journal of Near Infrared Spectroscopy*, 14(1): 1–14.

Ferreri, L., Bigand, E., Perrey, S. and Bugaiska, A. (2014). The promise of Near-Infrared Spectroscopy (NIRS) for psychological research: A brief review. *L'Année Psychologique*, 114(3): 537–569.

Ford, J. H., Giovanello, K. S. and Guskiewicz, K. M. (2013). Episodic memory in former professional football players with a history of concussion. *Journal of Neurotrauma*, 30(20): 1683–1701.

Fraas, M. R., Coughlan, G. F., Hart, E. C. and McCarthy, C. (2015). Concussion knowledge and management practices among coaches and medical staff in Irish professional rugby teams. *Irish Journal of Medical Science*, 184(2): 425–430.

Franceschini, M. A., Fantini, S., Thompson, J. H., Culver, J. P. and Boas, D. A. (2003). Hemodynamic evoked response of the sensorimotor cortex measured noninvasively with near-infrared optical imaging. *Psychophysiology*, 40(4): 548–560.

Frith, C. and Dolan, R. (1996). The role of the prefrontal cortex in higher cognitive functions. *Cognitive Brain Research*, 5(1–2): 175–181.

Gabrieli, J. D. E. (1998). Cognitive neuroscience of human memory. *Annual Review of Psychology*, 49(1): 87–115.

Gajawelli, N., Lao, Y., Apuzzo, M. L. J., Romano, R., Liu, C., Tsao, S., Hwang, D., Wilkins, B., Lepore, N. and Law, M. (2013). Neuroimaging changes in the brain in contact versus noncontact sport athletes using diffusion tensor imaging. *World Neurosurgery*, 80(6): 824–828.

Gardner, A. J., Iverson, G. L., Williams, W. H., Baker, S. and Stanwell, P. (2014). A systematic review and meta-analysis of concussion in Rugby Union. *Sports Medicine*, 44(12): 1717–1731.

Gardner, A. J., Iverson, G. L., Wojtowicz, M., Levi, C. R., Kay-lambkin, F., Schofield, P. W., Zafonte, R., Shultz, S. R., Lin, A. P. and Stanwell, P. (2017). MR spectroscopy findings in retired professional rugby league players. *International Journal of Sport Medicine*, 38(3): 241–252.

Gavett, B. E., Stern, R. A. and McKee, A. C. (2011). Chronic traumatic encephalopathy: A potential late effect of sport-related concussive and subconcussive head trauma. *Clinics in Sports Medicine*, 30(1): 179–188.

Gessel, L. M., Fields, S. K., Collins, C. L., Dick, R. W. and Comstock, R. D. (2007). Concussions among United States high school and collegiate athletes. *Journal of Athletic Training*, 42(4): 495–503.

Giedd, J. N. (2015). The Amazing Teen Brain. *Scientific American*, 312(6): 32–37.

Girouard, H., Iadecola, C., Chen, B. R., Kozberg, M. G., Bouchard, M. B., Shaik, M. A. and Hillman, M. C. (2014). Neurovascular coupling in the normal brain and in hypertension, stroke, and Alzheimer disease Regulation of the Cerebral Circulation Neurovascular coupling in the normal brain and in hypertension, stroke, and Alzheimer disease. *Journal of Applied Physiology*, 100(21): 328–335.

Giza, C. C. and Hovda, D. A. (2015). The new neurometabolic cascade of concussion. *Neurosurgery*, 33(4): 395–401.

Gomez-Pinilla, F. and Hillman, C. H. (2013). The influence of exercise on cognitive abilities. *Comprehensive Physiology*, 3(1): 403–428.

Gratton, G., Goodman-Wood, M. R. and Fabiani, M. (2001). Comparison of neuronal and hemodynamic measures of the brain response to visual stimulation: An optical imaging study. *Human Brain Mapping*, 13(1): 13–25.

Green, M. S., Sehgal, S. and Tariq, R. (2016). Near-infrared spectroscopy: The new must have tool in the intensive care unit. *Seminars in Cardiothoracic and Vascular Anesthesia*, 20(3): 213–224.

Gualtieri, C. T. and Johnson, L. G. (2006). Reliability and validity of a computerized neurocognitive test battery, CNS Vital Signs. *Archives of Clinical Neuropsychology*, 21(7): 623–643.

Handratta, V., Hsu, E., Vento, J., Yang, C. and Tanev, K. (2010). Neuroimaging findings and brain-behavioral correlates in a former boxer with chronic traumatic brain injury correlates in a former boxer with chronic traumatic brain injury. *Neurocase*, 16(2): 125–134.

Hart, J., Kraut, M. A., Womack, K. B., Strain, J., Didehbani, N., Bartz, E., Conover, H., Mansinghani, S., Lu, H. and Cullum, C. M. (2013). Neuroimaging of cognitive dysfunction and depression in aging retired National Football League players. *JAMA Neurology*, 70(3): 326–335.

Hartwig, T. B., Naughton, G. and Searl, J. (2011). Motion analyses of adolescent Rugby Union players: A comparison of training and game demands. *Journal of Strength & Conditioning Research*, 25(4): 966–972.

Hay, J., Johnson, V. E., Smith, D. H. and Stewart, W. (2016). Chronic traumatic encephalopathy: The neuropathological legacy of traumatic brain injury. *Annual Review of Pathology, Mechanisms of Disease*, 11(1): 21–45.

Hazrati, L., Tartaglia, M. C., Diamandis:, Davis, K. D., Green, R. E., Wennberg, R., Wong, J. C., Ezerins, L. and Tator, C. H. (2013). Absence of chronic traumatic encephalopathy in retired football players with multiple concussions and neurological symptomatology. *Frontiers in Human Neuroscience*, 7(May): 1–9.

Helmich, I., Saluja, R. S., Lausberg, H., Kempe, M., Furley, P., Berger, A., Chen, J. and Ptito, A. (2015). Persistent postconcussive symptoms are accompanied by decreased functional brain oxygenation. *Journal of Neuropsychiatry and Clinical Neuroscience*, 27(4): 287–298.

Hillman, C. H., Erickson, K. I. and Kramer, A. F. (2008). Be smart, exercise your heart: exercise effects on brain and cognition. *Nature Reviews Neuroscience*, 9(1): 58–65.

Hilti, C. C., Jann, K., Heinemann, D., Federspiel, A., Dierks, T., Seifritz, E. and Cattapan-Ludewig, K. (2013). Evidence for a cognitive control network for goal-directed attention in simple sustained attention. *Brain and Cognition*, 81(2): 193–202.

Hoffman, L. and Nixon, S. J. (2015). Alcohol doesn't always compromise cognitive function: Exploring moderate doses in young adults. *Journal of Studies on Alcohol and Drugs*, 76(6): 952–956.

Hopkins, W. G., Marshall, S. W., Batterham, A. M. and Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine and Science in Sports and Exercise*, 41(1): 3–12.

Huijgen, B. C. H., Leemhuis, S., Kok, N. M., Verburgh, L., Oosterlaan, J., Elferink-Gemser, M. T. and Visscher, C. (2015). Cognitive functions in elite and sub-elite youth soccer players aged 13 to 17 years. *PLoS ONE*, 10(12): 1–14.

Hume, P. A., Theadom, A., Lewis, G. N., Quarrie, K. L., Brown, S. R., Hill, R. and Marshall, S. W. (2017). A comparison of cognitive function in former Rugby Union players compared with former non-contact-sport players and the impact of concussion history. *Sports Medicine*, 47(6): 1209–1220.

Hwang, D. Y. and Golby, A. J. (2006). The brain basis for episodic memory: Insights from functional MRI, intracranial EEG, and patients with epilepsy. *Epilepsy & Behaviour*, 8(1): 115–126.

Hwang, M., Tudorascu, D. L., Nunley, K., Karim, H., Aizenstein, H. J., Orchard, T. J. and Rosano, C. (2016). Brain activation and psychomotor speed in middle-aged patients with type 1 diabetes: Relationships with hyperglycemia and brain small vessel disease. *Journal of Diabetes Research*, ID 9571464: 1–11.

Jackson, A. S. and Pollock, M. L. (1978). Generalized equations for predicting body density of men. *British Journal of Nutrition*, 40(3): 497-504.

Jacobson, J. and Matthaeus, L. (2014). Athletics and executive functioning: How athletic participation and sport type correlate with cognitive performance. *Psychology of Sport and Exercise*. 15(5): 521–527.

Jansen, A., Sehlmeyer, C., Pfleiderer, B., Sommer, J., Konrad, C., Zwitserlood, P. and Knecht, S. (2009). Assessment of verbal memory by fMRI: Lateralization and functional neuroanatomy. *Clinical Neurology and Neurosurgery*, 111(1): 57–62.

Jelicic, M., Gearaerts, E., Merkelbach, H. and Guerrieri, R. (2004). Acute stress enhances memory for emotional words, but impairs memory for neutral words. *International Journal of Neuroscience*, 114(10): 1343–1351.

Jöbsis, F. F. (1977). Noninvasive, infrared monitoring of cerebral and myocardial oxygen sufficiency and circulatory parameters. *American Association for the Advancement of Science*, 198(4323): 1264–1267.

Johnson, B., Neuberger, T., Gay, M., Hallett, M. and Slobounov, S. (2014). Effects of subconcussive head trauma on the default mode network of the brain. *Journal of Neurotrauma*, 31(23): 1907–1913.

Jones, D. K. and Leemans, A. (2011). Diffusion Tensor Imaging. *Methods in Molecular Biology*, 7(11): 127–144.

Jordan, B. D. (2009). Brain Injury in Boxing. *Clinics in Sports Medicine*, 28(4): 561–578.

Jurcak, V., Tsuzuki, D. and Dan, I. (2007). 10/20, 10/10, and 10/5 systems revisited: Their validity as relative head-surface-based positioning systems. *NeuroImage*, 34(4): 1600–1611.

Kang, S., Yoon, H., Cho, C., Kwon, S., Kang, J., Park, Y., Lee, E., Kim, L. and Lee, H. (2016). Decrease in fMRI brain activation during working memory performed after sleeping under 10 lux light. *Scientific Reports*, 6: 36731.

Kenttä, G., Hassmen, P., Raglin, J. S. (2006). Mood state monitoring of training and recovery in elite kayakers. *European Journal of Sport Science*, 6(4): 245 – 253.

Kida, N., Oda, S. and Matsumura, M. (2005). Intensive baseball practice improves the Go/Nogo reaction time, but not the simple reaction time. *Cognitive Brain Research*, 22(2): 257–264.

Killam, C., Cautin, R. L. and Santucci, A. C. (2005). Assessing the enduring residual neuropsychological effects of head trauma in college athletes who participate in contact sports. *Archives of Clinical Neuropsychology*, 20(5): 599–611.

Kim, C., Johnson, N. F., Cilles, S. E. and Gold, B. T. (2011). Common and distinct mechanisms of cognitive flexibility in prefrontal cortex. *The Journal of neuroscience: the official journal of the Society for Neuroscience*, 31(13): 4771–4779.

King, D., Hume, P. A., Brughelli, M. and Gissane, C. (2014). Instrumented mouthguard acceleration analyses for head impacts in amateur Rugby Union players over a season of matches. *American Journal of Sports Medicine*, 43(3): 614–624.

Koerte, I. K., Ertl-Wagner, B., Reiser, M., Zafonte, R. and Shenton, M. E. (2012). White matter integrity in the brains of professional soccer players without a symptomatic concussion. *Journal of the American Medical Association*, 308(18): 1859–1861.

Koerte, I. K., Mayinger, M., Muehlmann, M., Kaufmann, D., Lin, A. P., Steffinger, D., Fisch, B., Rauchmann, B., Immler, S., Karch, S., Heinen, F. R., Ertl-wagner, B., Reiser, M., Stern, R. A., Zafonte, R. and Shenton, M. E. (2016). Cortical thinning in former professional soccer players. *Brain Imaging and Behavior*, 10(3): 792–798.

Kofman, O., Meiran, N., Greenberg, E., Balas, M. and Cohen, H. (2006). Enhanced performance on executive functions associated with examination stress: Evidence from task-switching and Stroop paradigms. *Cognition and Emotion*, 20(5): 577–595.

Kontos, A. P., Huppert, T. J., Beluk, N. H., Elbin, R. J., Henry, L. C., French, J., Dakan, S. M. and Collins, M. W. (2014). Brain activation during neurocognitive testing using functional near-infrared spectroscopy in patients following concussion compared to healthy controls. *Brain Imaging and Behavior*, 8(4): 621–634.

Kreutzmann, J. C., Havekes, R., Abel, T. and Meerlo, P. (2015). Sleep deprivation and hippocampal vulnerability: Changes in neuronal plasticity, neurogenesis and cognitive function. *Neuroscience*, 309: 173–190.

Leber, A. B., Turk-Browne, N. B. and Chun, M. M. (2008). Neural predictors of moment-to-moment fluctuations in cognitive flexibility. *Proceedings of the National Academy of Sciences*, 105(36): 13592–13597.

Lee, J., Folley, B. S., Gore, J. and Park, S. (2008). Origins of spatial working memory deficits in schizophrenia: An event-related fMRI and near-infrared spectroscopy study. *PLoS ONE*, 3(3): 1–11.

Lee, M. H., Smyser, C. D. and Shimony, J. S. (2013). Resting-state fMRI: A review of methods and clinical applications. *American Journal of Neuroradiology*, 34(10): 1866–1872.

Lee, S., Kawachi, I., Berkman, L. F. and Grodstein, F. (2003). Education, other socioeconomic indicators, and cognitive function. *American Journal of Epidemiology*, 157(8): 712–720.

León-Carrion, J., Damas-López, J., Martín-Rodríguez, J. F., Domínguez-Roldán, J. M., Murillo-Cabezas, F., Barroso, J. M. and Domínguez, M. R. (2008). The hemodynamics of cognitive control: The level of concentration of oxygenated hemoglobin in the superior prefrontal cortex varies as a function of performance in a modified Stroop task. *Behavioural Brain Research*, 193(2): 248–256.

Lipton, M. L., Namhee, K., Zimmerman, M. E., Kim, M., Stewart, W. F., Branch, C. A. and Lipton, R. B. (2013). Soccer heading associated with white matter microstructural and cognitive abnormalities. *Radiology*, 268(3): 850–857.

Lucke-Wold, B. P., Turner, R. C., Logsdon, A. F., Bailes, J. E., Huber, J. D. and Rosen, C. L. (2014). Linking traumatic brain injury to chronic traumatic encephalopathy: Identification of potential mechanisms leading to neurofibrillary tangle development. *Journal of Neurotrauma*, 31(13): 1129–1138.

Lynch, J. M., Buckley, E. M., Schwab: J., Busch, D. R., Hanna, B. D., Putt, M. E., Licht, D. J. and Yodh, A. G. (2014). Noninvasive optical quantification of cerebral venous oxygen saturation in humans. *Academic Radiology*, 21(2): 162–167.

MacDonald, L. A. and Minahan, C. L. (2016). Indices of cognitive function measured in rugby union players using a computer-based test battery. *Journal of Sports Sciences*, 34(17): 1669–1674.

Madsen, P. L. and Secher, N. H. (1999). Near-infrared oximetry of the brain. *Progress in Neurobiology*, 58(6): 541–560.

Maroon, J. C., Winkelman, R., Bost, J., Amos, A., Mathyssek, C. and Miele, V. (2015). Chronic traumatic encephalopathy in contact sports: A systematic review of all reported pathological cases. *PLoS ONE*, 10(2): 1–17.

Matsui, M., Tanaka, K., Yonezawa, M. and Kurachi, M. (2007). Activation of the prefrontal cortex during memory learning: Near-infrared spectroscopy study. *Psychiatry and Clinical Neurosciences*, 61(1): 31–38.

Mc Fie, S., Brown, J., Hendricks, S., Posthumus, M., Readhead, C., Lambert, M., September, A. and Viljoen, W. (2016). The incidence and factors associated with concussion injuries at the 2011 – 2014 South African Rugby Union youth week tournaments. *Clinical Journal of Sport Medicine*, 26(5): 398–404.

McCrory, P. R. and Berkovic, S. F. (1998). Second impact syndrome. *Neurology*, 50(3): 677–683.

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

McCrory, P., Meeuwisse, W. H., Aubry, M., Cantu, R. C., Dvorák, J., Echemendia, R. J., Engebretsen, L., Johnston, K. M., Kutcher, J. S., Raftery, M., Sills, A., Benson, B. W., Davis, G. A., Ellenbogen, R., Guskiewicz, K. M., Herring, S. A., Iverson, G. L., Jordan, B. D., Kissick, J., McCrea, M., McIntosh, A. S., Maddocks, D. L., Makdissi, M., Purcell, L., Putukian, M., Schneider, K., Tator, C. H. and Turner, M. (2013). Consensus statement on concussion in sport-The 4th International Conference on Concussion in Sport held in Zurich, November 2012. *British Journal of Sports Medicine*, 5(4): 255–279.

McCrory, P., Meeuwisse, W., Dvorak, J., Aubry, M., Bailes, J., Broglio, S., Cantu, R. C., Cassidy, D., Echemendia, R. J., Castellani, R. J., Davis, G. A., Ellenbogen, R., Emery, C., Engebretsen, L., Feddermann-Demont, N., Giza, C. C., Guskiewicz, K. M., Herring, S., Iverson, G. L., Johnston, K. M., Kissick, J., Kutcher, J., Leddy, J. J., Maddocks, D., Makdissi, M., Manley, G. T., McCrea, M., Meehan, W. P., Nagahiro, S., Patricios, J., Putukian, M., Schneider, K. J., Sills, A., Tator, C. H., Turner, M. and Vos, P. E. (2017). Consensus statement on concussion in sport—the 5 th international conference on concussion in sport held in Berlin, October 2016. *British Journal of Sports Medicine*, 51(11): 838–847.

McEwen, B. S. and Sapolsky, R. M. (1995). Stress and cognitive function. *Current Opinion in Neurobiology*, 5(2): 205–216.

McIntosh, A. S., McCrory, L., Finch, C. F., Best, J. P., Chalmers, D. J. and Wolfe, R. (2009). Does padded headgear prevent head injury in rugby union football? *Medicine and Science in Sports and Exercise*, 41(2): 306–313.

McKee, A. C., Stein, T. D., Kiernan, P. T. and Alvarez, V. E. (2015). The neuropathology of chronic traumatic encephalopathy. *Brain Pathology*, 25(3): 350–364.

McKee, A. C., Stein, T. D., Nowinski, C. J., Stern, R. A., Daneshvar, D. H., Alvarez, V. E., Lee, H. S., Hall, G., Wojtowicz, S. M., Baugh, C. M., Riley, D. O., Kubilus, C. A., Cormier, K. A., Jacobs, M. A., Martin, B. R., Abraham, C. R., Ikezu, T., Reichard, R. R., Wolozin, B. L., Budson, A. E., Goldstein, L. E., Kowall, N. W. and Cantu, R. C. (2013). The spectrum of disease in chronic traumatic encephalopathy. *Brain*, 136(1): 43–64.

McMillan, T. M., McSkimming, P., Wainman-Lefley, J., Maclean, L. M., Hay, J., McConnachie, A. and Stewart, W. (2017). Long-term health outcomes after exposure to repeated concussion in elite level: Rugby Union players. *Journal of Neurology, Neurosurgery & Psychiatry*, 88(6): 505–512.

Meehan, W. P., Mannix, R. C., O'brien, M. J. and Collins, M. W. (2013). The Prevalence of Undiagnosed Concussions in Athletes. *Clinical Journal of Sport Medicine J Sport Med*, 23(5): 339–342.

Meek, A. J. H., Elwell, C. E., Khan, M. J., Romaya, J., Wyatt, J. S., Delpy, D. T., Proceedings, S., Sciences, B. and Sep, N. (1995). Regional changes in cerebral haemodynamics as a result of a visual stimulus measured by near infrared spectroscopy. *Proceedings of the Royal Society of London. Series B: Biological Sciences*, 261(1362): 351–356.

Mendl, M. (1999). Performing under pressure: Stress and cognitive function. *Applied Animal Behaviour Science*, 65(3): 221–244.

Messé, A., Caplain, S., Pélégrini-Issac, M., Blancho, S., Lévy, R., Aghakhani, N., Montreuil, M., Benali, H. and Lehéricy, S. (2013). Specific and evolving resting-state network alterations in post-concussion syndrome following mild traumatic brain injury. *PLoS ONE*, 8(6). pp. 1–10.

Miller, E. K. and Wallis, J. D. (2009). Executive function and higher-order cognition: Definition and neural substrates. *Encyclopedia of Neuroscience*: 99–104.

Minati, L., Kress, I. U., Visani, E., Medford, N. and Critchley, H. D. (2011). Intra- and extra-cranial effects of transient blood pressure changes on brain near-infrared spectroscopy (NIRS) measurements. *Journal of Neuroscience Methods*, 197(2): 283–288.

Moore, R. D., Lepine, J. and Ellemberg, D. (2017). The independent influence of concussive and sub-concussive impacts on soccer players' neurophysiological and neuropsychological function. *International Journal of Psychophysiology*. 112(February): 22–30.

Moriarity, J., Collie, A., Olson, D., Buchanan, J., Leary:, McStephen, M. and McCrory, P. (2004). A prospective controlled study of cognitive function during an amateur boxing tournament. *Neurology*, 62(9): 1497–1502.

Mukaka, M. M. (2012). A guide to appropriate use of correlation coefficient in medical research. *Malawi Medical Journal*, 24(3): 69–71.

Murata, Y., Sakatani, K., Hoshino, T., Fujiwara, N., Kano, T., Nakamura, S. and Katayama, Y. (2006). Effects of cerebral ischemia on evoked cerebral blood oxygenation responses and BOLD contrast functional MRI in stroke patients. *Stroke*, 37(10): 2514–2520.

Murata, Y., Sakatani, K., Katayama, Y. and Fukaya, C. (2002). Increase in focal concentration of deoxyhaemoglobin during neuronal activity in cerebral ischaemic patients. *Journal of Neurology, neurosurgery, and psychiatry*, 73(2): 182–184.

Myer, G. D., Yuan, W., Foss, K. D. B., Thomas, S., Smith, D., Leach, J., Kiefer, A. W., Dicesare, C., Adams, J., Gubanich, P. J., Kitchen, K., Schneider, D. K., Braswell, D., Krueger, D. and Altaye, M. (2016). Analysis of head impact exposure and brain microstructure response in a season-long application of a jugular vein compression collar: A prospective, neuroimaging investigation in American football. *British Journal of Sports Medicine*, 50(20): 1276–1285.

Nagdyman, N., Fleck, T., Barth, S., Abdul-Khaliq, H., Stiller, B., Ewert, P., Huebler, M., Kuppe, H. and Lange: E. (2004). Relation of cerebral tissue oxygenation index to central venous oxygen saturation in children. *Intensive Care Medicine*, 30(3): 468–471.

Nagdyman, N., Fleck, T., Schubert, S., Ewert, P., Peters, B., Lange, P. E. and Abdul-Khaliq, H. (2005). Comparison between cerebral tissue oxygenation index measured by near-infrared spectroscopy and venous jugular bulb saturation in children. *Intensive Care Medicine*, 31(6): 846–850.

Nauman, E. A., Breedlove, K. M., Breedlove, E. L., Talavage, T. M., Robinson, M. E. and Leverenz, L. J. (2015). Post-season neurophysiological deficits assessed by ImPACT and fMRI in athletes competing in American football. *Developmental Neuropsychology*, 40(2): 85–91.

Navarro, R. R. (2011). Protective equipment and the prevention of concussion - what is the evidence? *Current Sports Medicine Reports*, 10(1): 27–31.

O'Connell, E. and Molloy, M. G. (2016). Concussion in rugby: Knowledge and attitudes of players. *Irish Journal of Medical Science*, 185(2): 521–528.

Okada, E. and Delpy, D. T. (2003). Near-infrared light propagation in an adult head model. I. Modeling of low-level scattering in the cerebrospinal fluid layer. *Applied Optics*, 42(16): 2906–2914.

Okada, E., Yamamoto, D., Kiryu, N. and Katagiri, A. (2010). Theoretical and experimental investigation of the influence of frontal sinus on the sensitivity of the NIRS signal in the adult head. *Advances in Experimental and Medical Biology*, 662: 231–236.

Omalu, B. I., DeKosky, S. T., Hamilton, R. L., Minster, R. L., Kamboh, M. I., Shakir, A. M. and Wecht, C. H. (2006). Chronic traumatic encephalopathy in a National Football League player: Part II. *Neurosurgery*, 59(5): 1086–1092.

Omalu, B. I., DeKosky, S. T., Minster, R. L., Kamboh, M. I., Hamilton, R. L. and Wecht, C. H. (2005). Chronic traumatic encephalopathy in a National Football League player. *Neurosurgery*, 57(1): 128–133.

Pardo, J. V, Fox, P. T. and Raichle, M. E. (1991). Localization of a human system for sustained attention by positron emission tomography. *Nature*, 349(6304): 61–64.

Pascual-Leone, A., Freitas, C., Oberman, L., Horvath, J. C., Halko, M., Eldaief, M., Bashir, S., Vernet, M., Shafi, M., Westover, B., Vahabzadeh-Hagh, A. M. and Rotenberg, A. (2011). Characterizing brain cortical plasticity and network dynamics across the age-span in health and disease with TMS-EEG and TMS-fMRI. *Brain Topography*, 24(3–4): 302–315.

Patricios, J. S., Kohler, R. M. N. and Collins, R. M. (2010). Sports-related concussion relevant to the South African rugby environment-a review. *South African Journal of Sports Medicine*, 22(4): 88–94.

Paulus, R., Roth, A., Titus, L., Chen, R., Bridges, M. C. and Woodyard, S. (2015). Impact of various caffeine vehicles on mood and cognitive, neurpological and physiological functions over five hours. *Ohio Journal of Science*, 115(2) 51–62.

Petersen, S. E. and Posner, M. (2012). The attention system of the human brain: 20 years after. *Annual Review of Neuroscience*, 21(35): 73–89.

Phelps, M. E. (2000). Positron emission tomography provides molecular imaging of biological processes. *Proceedings of the National Academy of Sciences of the United States of America*, 97(16): 9226–9233.

Poldrack, R. A. and Gabrieli, J. D. E. (1998). Memory and the brain: What's right and what's left? *Cell*, 93(7): 1091–1093.

Poltavski, D. V, Marino, J. M., Guido, J. M., Kulland, A. and Petros, T. V. (2011). Effects of acute alcohol intoxication on verbal memory in young men as a function of time of day. *Physiology & Behavior*, 102(1): 91–95.

Poole, V., Abbas, K., Shenk, T. E., Breedlove, E. L., Breedlove, K. M., Robinson, M. E., Leverenz, L. J., Nauman, E. A., Talavage, T. M. and Dydak, U. (2015). Sub-concussive hit characteristics predict deviant brain metabolism in football athletes MR spectroscopic evidence of brain injury. *Developmental Neuropsychology*, 39(6): 459–473.

Posner, M. I. and Rothbart, M. K. (1998). Attention, self-regulation and consciousness. *Philosophical Transactions: Biological Sciences*, 353(1377): 1915–1927.

Provenzano, F. A., Jordan, B., Tikofsky, R. S., Saxena, C., Heertum, R. L. Van and Ichise, M. (2010). F-18 FDG PET imaging of chronic traumatic brain injury in boxers : a statistical parametric analysis. *Nuclear Medicine Communications*, 31(11): 952–957.

Raftery, M. (2014). Concussion and chronic traumatic encephalopathy: International Rugby Board's response. *British Journal of Sports Medicine*, 48(2): 79–80.

Reuter-Lorenz, P. A. and Campbell, K. A. (2008). Neurocognitive ageing and the compensation hypothesis. *Current Directions in Psychological Science*, 17(3): 177–182.

Reuter-Lorenz, P. A. and Park, D. C. (2010). Human neuroscience and the aging mind: A new look at old problems. *Journals of Gerontology Series B-Psychological Sciences and Social Sciences*, 65(4): 405–415.

Richardson, C., Atkins, S., Hurst, H., Quinn, M. and Sinclair, J. (2017). Executive function testing to assist identification of pitch-side concussion in elite rugby players. *The Lancet*, 389: S83.

Rochette, A. D., Spitznagel, M. B., Strain, G., Devlin, M., Crosby, R. D., Mitchell, J. E., Courcoulas, A. and Gunstad, J. (2016). Mild cognitive impairment is prevalent in persons with severe obesity. *Obesity*, 24(7): 1427–1429.

Rodrigues, A. C., Lasmar, R. P., Caramelli, P., Stern, R. A., Graeber, M. B. and Caramelli, P. (2016). Effects of Soccer Heading on Brain Structure and Function. *Frontiers in Neurology*, 7: 1–11.

Rolfe, P. (2000). In vivio near-infrared spectroscopy. *Annual Review of Biomedical Engineering*, 2(8): 715–54.

Ryan, L. M. and Warden, D. L. (2003). Post concussion syndrome. *International Review of Psychiatry*, 15(4): 310–316.

Sakatani, K., Yamashita, D., Yamanaka, T., Oda, M., Yamashita, Y., Hoshino, T., Fujiwara, N., Murata, Y. and Katayama, Y. (2006). Changes of cerebral blood oxygenation and optical pathlength during activation and deactivation in the prefrontal cortex measured by time-resolved near infrared spectroscopy. *Life Sciences*, 78(23): 2734–2741.

Schroeter, M. L., Zysset, S., Kupka, T., Kruggel, F. and Von Cramon, D. Y. (2002). Near-infrared spectroscopy can detect brain activity during a color-word matching stroop task in an event-related design. *Human Brain Mapping*, 17(1): 61–71.

Schroeter, M. L., Zysset, S., Wahl, M. and Von Cramon, D. Y. (2004). Prefrontal activation due to Stroop interference increases during development - An event-related fNIRS study. *NeuroImage*, 23(4): 1317–1325.

Sedeaud, A., Marc, A., Schipman, J., Tafflet, M., Hager, J. and Toussaint, J. (2012). How they won Rugby World Cup through height, mass and collective experience. *British Journal of Sports Medicine*, 46(8): 580–584.

Seichepine, D. R., Stamm, J. M., Daneshvar, D. H., Riley, D. O., Baugh, C. M., Gavett, B. E., Tripodis, Y., Martin, B., Chaisson, C., McKee, A. C., Cantu, R. C., Nowinski, C. J. and Stern, R. A. (2013). Profile of self-reported problems with executive functioning in college and professional football players. *Journal of Neurotrauma*, 30(14): 1299–1304.

Shang, C. Y. and Gau, S. S. (2011). Visual memory as a potential cognitive endophenotype of attention deficit hyperactivity disorder. *Psychological Medicine*, 41(12): 2603–2614.

Shenk, T. E., Robinson, M. E., Svaldi, D. O., Breedlove, K. M., Leverenz, L. J. and Nauman, E. A. (2015). fMRI of visual working memory in high school football players. *Developmental Neuropsychology*, 40(2): 63–68.

Sherwood, L. (2012). *Introduction to human physiology*. 8th Edition. Boston, MA: Thomson Brooks/Cole.

Shields, G. S., Sazma, M. A. and Yonelinas, A. P. (2016). The effects of acute stress on core executive functions: A meta-analysis and comparison with cortisol. *Neuroscience and Biobehavioral Reviews*, 68: 651–668.

Shuttleworth-Edwards, A. B. and Radloff, S. E. (2008). Compromised visuomotor processing speed in players of Rugby Union from school through to the national adult level. *Archives of Clinical Neuropsychology*, 23(5): 511–520.

Shuttleworth-Edwards, A. B., Smith, I. and Radloff, S. E. (2008). Neurocognitive vulnerability amongst university rugby players versus noncontact sport controls. *Journal of Clinical and Experimental Neuropsychology*, 30(8): 870–884.

Signoretti, S., Lazzarino, G., Tavazzi, B. and Vagnozzi, R. (2011). The pathophysiology of concussion. *American Academy of Physical Medicine and Rehabilitation*, 3(2): S359–S368.

Simmons, S., Bernick, C., Banks, S. and Obuchowski, N. (2013). The effect of age of starting a contact sport on subsequent brain volumes. *Alzheimer's and Dementia*, 9(4): 838–839.

Slobounov, S. M., Walter, A., Breiter, H. C., Zhu, D. C., Bai, X., Bream, T., Seidenberg, P., Mao, X., Johnson, B. and Talavage, T. M. (2017). The effect of repetitive subconcussive collisions on brain integrity in collegiate football players over a single football season: A multi-modal neuroimaging study. *NeuroImage: Clinical*, 14(1): 708–718.

Slotnick, S. D. (2004). Visual memory and visual perception recruit common neural substrates. *Behavioral and Cognitive Neuroscience Reviews*, 3(4): 207–221.

Smeets, T., Jelicic, M. and Merckelbach, H. (2006). The effect of acute stress on memory depends on word valence. *International Journal of Psychophysiology*, 62(1): 30–37.

Smith, D. W., Bailes, J. E., Fisher, J. A., Robles, J., Turner, R. C. and Mills, J. D. (2011). Internal jugular vein compression mitigates traumatic axonal injury in rat model by reducing intracranial slosh effect. *Neurosurgery*, 70(3): 740–746.

Smith, E., Jonides, J. and Koeppe, R. A. (1996). Dissociating verbal and spatial working memory using PET. *Cerebral Cortex*, 6(1): 11–20.

Smith-Ryan, A. E., Fultz, S. N., Melvin, M. N., Wingfield, H. L. and Woessner, M. N. (2014). Reproducibility and validity of A-mode ultrasound for body composition measurement and classification in overweight and obese men and women. *PLoS ONE*, 9(3): e91750.

Stamm, J. M., Bourlas, A. P., Baugh, C. M., Fritts, N. G., Daneshvar, D. H., Martin, B. M., McClean, M. D., Tripodis, Y. and Stern, R. A. (2015). Age of first exposure to football and later-life cognitive impairment in former NFL players. *Neurology*, 84(11): 1114–1120.

Stephens, R., Rutherford, A., Potter, D. and Fernie, G. (2010). Neuropsychological consequence of soccer play in adolescent U.K. School team soccer players. *The Journal of Neuropsychiatry and Clinical Neurosciences*, 22(3): 295–303.

Stern, R. A., Riley, D. O., Daneshvar, D. H., Nowinski, C. J., Cantu, R. C. and McKee, A. C. (2011). Long-term consequences of repetitive brain trauma: Chronic traumatic encephalopathy. *American Academy of Physical Medicine and Rehabilitation*, 3(2): S460–S467.

Stojsih, S., Boitano, M., Wilhelm, M. and Bir, C. (2010). A prospective study of punch biomechanics and cognitive function for amateur boxers. *British Journal of Sports Medicine*, 44(10): 725–730.

Strangman, G., Franceschini, M. A. and Boas, D. A. (2003). Factors affecting the accuracy of near-infrared spectroscopy concentration calculations for focal changes in oxygenation parameter. *Neurology*, 18(4): 865–879.

Svaldi, D. O., Robinson, M. E., Nauman, E. A. and Leverenz, L. J. (2015). Cerebrovascular Reactivity Alterations in Asymptomatic High School Football Players. *Developmental Neuropsychology*, 40(2): 80–84.

Talavage, T. M., Nauman, E. A., Breedlove, E. L., Yoruk, U., Dye, A. E., Morigaki, K., Feuer, H. and Leverenz, L. J. (2014). Functionally-detected cognitive impairment in high school football players without clinically diagnosed concussion. *Journal of Neurotrauma*, 338(765): 1–46.

Tator, C. H. (2014). Chronic traumatic encephalopathy: How serious a sports problem is it? *British journal of sports medicine*, 48: 81–83.

Terry, P. C., Potgieter, J. R. amd Fogarty, G. J. (2003). The stellenbosch mood scale: A dual-language measure of mood. *International Journal of Sport and Exercise Psychology*, 1(3): 231–245

Thornton, A. E., Cox, D. N., Whitfield, K. and Fouladi, R. T. (2008). Cumulative concussion exposure in rugby players: Neurocognitive and symptomatic outcomes. *Journal of Clinical and Experimental Neuropsychology*, 30(4): 398–409.

Toichi, M., Findling, R. L., Kubota, Y., Calabrese, J. R., Wiznitzer, M., McNamara, N. K. and Yamamoto, K. (2004). Hemodynamic differences in the activation of the prefrontal cortex: Attention vs. higher cognitive processing. *Neuropsychologia*, 42(5): 698–706.

Turner, R. C., Naser, Z. J., Bailes, J. E., Smith, D. W., Fisher, J. A. and Rosen, C. L. (2012). Effect of slosh mitigation on histologic markers of traumatic brain injury. *Journal of Neurosurgery*, 117: 1110–1118.

Vestberg, T., Gustafson, R., Maurex, L., Ingvar, M. and Petrovic, P. (2012). Executive functions predict the success of top-soccer players. *PLoS ONE*, 7(4): 1–6.

Villringer, A. and Chance, B. (1997). Non-invasive optical spectroscopy and imaging of human brain function. *Trends in Neurosciences*, 20(10): 435–442.

Verhaeghen, P. and Salthouse, T. A. (1997). Meta-analyses of age-cognition relations in adulthood: Estimates of linear and nonlinear age effects and structural models. *Psychological Bulletin*, 122(3): 231–249.

Voelcker-Rehage, C., Godde, B. and Staudinger, U. M. (2011). Cardiovascular and coordination training differentially improve cognitive performance and neural processing in older adults. *Frontiers in Human Neuroscience*, 5(26): 1–12.

Walker, M. P. and Stickgold, R. (2004). Sleep-dependent learning and memory consolidation. *Neuron*, 44(1): 121–133.

Walker, S. P. (2015). Concussion knowledge and return-to-play attitudes among subelite rugby union players. *South African Journal of Sports Medicine*, 27(2): 50–54.

Wassenaar, E. B. and Van den Brand, J. G. H. (2005). Reliability of near-infrared spectroscopy in people with dark skin pigmentation. Journal of Clinical Monitoring and Computing, 19(3): 195–199.

Weissenborn, R. and Duka, T. (2003). Acute alcohol effects on cognitive function in social drinkers: their relationship to drinking habits. *Psychopharmacology*, 165(3): 306–312.

Williams, R. M., Puetz, T. W., Giza, C. C. and Broglio, S. P. (2015). Concussion recovery time among high school and collegiate athletes: A systematic review and meta-analysis. *Sports Medicine*, 45(6): 893–903.

Witt, S. T., Meyerand, M. E. and Laird, A. R. (2009). Functional neuroimaging correlates of finger tapping task variations: An ALE meta-analysis. *Neuroimage*, 42(1): 343–356.

Wixted, J. T. and Squire, L. R. (2011). The medial temporal lobe and the attributes of memory. *Trends in Cognitive Sciences*, 15(5): 210–217.

Wong, A. L., Haith, A. M. and Krakauer, J. W. (2015). Motor planning. *The Neuroscientist*, 21(4): 385–398.

Wrold Rugby, 2016. *World Rugby Year in Review 2016*.

Yoshitani, K., Kawaguchi, M., Miura, N., Okuno, T., Kanoda, T., Ohnishi, Y. and Kuro, M. (2007). Effects of hemoglobin concentration, skull thickness, and the area of the cerebrospinal fluid layer on near-infrared spectroscopy measurements. *Anesthesiology*, 106(3): 458–462.

Zhang, M. R., Red, S. D., Lin, A. H., Patel, S. S. and Sereno, A. B. (2013). Evidence of cognitive dysfunction after soccer playing with ball heading using a novel tablet-based approach. *PLoS ONE*, 8(2): 8–11.

APPENDIX A

UNIVERSITEIT•STELLENBOSCH•UNIVERSITY
jou kennisvennoot • your knowledge partner

STELLENBOSCH UNIVERSITY
CONSENT TO PARTICIPATE IN RESEARCH

Changes in cognitive function and cerebral oxygenation patterns in contact and non-contact sportspersons over a 12-week season.

You are asked to participate in a research study conducted by Anthony Clark (BSc Honours Sport Science), from the Department of Sport Science at Stellenbosch University. Your participation will contribute to an MSc thesis. You were selected as a possible participant in this study because you are either a member of the Stellenbosch University 2017 Varsity Cup Rugby squad or participate in a non-contact sport for Stellenbosch University.

1. PURPOSE OF THE STUDY

The purpose of the study is to assess the acute effects of physical contact on the brains of players who participate in a high level competition.

2. PROCEDURES

If you volunteer to participate in this study, we would ask you to do the following things:

1. Visit the Sport Physiology laboratory on two occasions, before and after the Varsity Cup Rugby competition, or before and after a 12 week period in case you're in the control group, for the assessment of your body composition, cognitive function and blood flow in your brain. All these tests are non-invasive and will last approximately one hour.
2. Complete questionnaires on selected personal information, your health, your sleep quantity and quality and your mental mood states.
3. If you are a rugby player, we will ask permission that we obtain your fitness and fatigue scores for the Yo-Yo and HIMS tests from your team's strength and conditioning coach. You will perform these tests as part of your training.
4. If you are not a rugby player, and participate as a control subject in this study, you will perform a Yo-Yo and HIMS test at the beginning and end of the 12 week period at the Department of Sport Science. The Yo-Yo test assesses your endurance fitness and the HIMS assesses your physical fatigue.
5. Prior to each testing session you will be required to consume no alcohol and no caffeine for 24 hours and 12 hours, respectively. You will also be asked to avoid any use of your cell phone, iPad or tablet for 6 hours prior to testing. The night before each test you must please get a good night's sleep of at least 6 hours. If any of these conditions are not met we will simply reschedule the test for the following day.

3. POTENTIAL RISKS AND DISCOMFORTS

The study does not use any invasive measurement procedures, thus there is minimal risk for participation. The Yo-yo Intermittent test is a maximal aerobic test and thus you may experience some discomfort during or after the test. However, this will not be any different from what you experience during a hard training session.

4. POTENTIAL BENEFITS TO SUBJECTS AND/OR TO SOCIETY

Participation in the study does not contain any direct benefit to you as a sportsperson. However you will be aiding in the contribution to the scientific body of literature on head injuries and the potential risks of repetitive physical contacts in sports such as rugby.

5. PAYMENT FOR PARTICIPATION

There is no payment for participation in this study.

6. CONFIDENTIALITY

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission or as required by law. Confidentiality will be maintained by means of storing all data on a secure computer with no public access. Only the researcher will have access to the raw data. Participants' names, personal details (birthdate, contact details etc.) and test results will not be used in the data analysis and will not appear in any publications or be made available to the public by any means. The results of this study will be analysed collectively and only group findings will be published.

7. PARTICIPATION AND WITHDRAWAL

You can choose whether to be in this study or not. If you volunteer to be in this study, you may withdraw at any time without consequences of any kind. Your participation, or not, in this study will have no bearing on your position within the team, or your position in your sport club. You may also refuse to answer any questions you don't want to answer and still remain in the study. The investigator may withdraw you from this research if circumstances arise which warrant doing so. For instance, if you suffer a diagnosed concussion or an injury that excludes you from training/matches for more than 2 weeks during the course of the study then you will be withdrawn from the study

8. IDENTIFICATION OF INVESTIGATORS

If you have any questions or concerns about the research, please feel free to contact:

Lead Researcher:

- Anthony Clark
- Email: [redacted]
- Phone: [redacted]

Supervisor:

- Prof. Elmarie Terblanche
- Email: [redacted]
- Phone: [redacted]

9. RIGHTS OF RESEARCH SUBJECTS

You may withdraw your consent at any time and discontinue participation without penalty. You are not waiving any legal claims, rights or remedies because of your participation in this research study. If you have questions regarding your rights as a research subject, contact Ms Maléne Fouché [mfouche@sun.ac.za; 021 808 4622] at the Division for Research Development.

SIGNATURE OF RESEARCH SUBJECT OR LEGAL REPRESENTATIVE

The information above was described to me by Anthony Clark in English and I, _____, am in command of this language or it was satisfactorily translated to me. I was given the opportunity to ask questions and these questions were answered to my satisfaction.

I hereby consent voluntarily to participate in this study. I have been given a copy of this form.

_____

Name of Subject/Participant

_____

Name of Legal Representative (if applicable)

_____ _____

Signature of Subject/Participant or Legal Representative **Date**

SIGNATURE OF INVESTIGATOR

I declare that I explained the information given in this document to _____ . He was encouraged and given ample time to ask me any questions. This conversation was conducted in _____ and no translator was used.

_____ _____

Signature of Investigator **Date**

APPENDIX B

Personal Details		
Name		
Age		
Degree		
Sport		
Highest level of participation?	National	Provincial
	Junior Provincial	Club
Years in Maties 1st/2nd team?		
Position?		
Training sessions per week?		
Other sports?		
Did you consume alcohol in the past 24 hours?		
Have you consumed any caffeine today?		
Are you currently taking any chronic (long term) medication?		
Hours of Sleep?		
Quality of Sleep?	1 2 3 4 5	
Height (do not fill in)		
Weight (do not fill in)		

APPENDIX C

Health Status Questionnaire

On this questionnaire, a number of questions regarding your physical health are to be answered. Please answer every question as accurately as possible so that a correct assessment can be made. Please mark the space to the left of the question to answer "yes". Leave blank if your answer is "no". Please ask if you have any questions. Your response will be treated in a confidential manner.

Name:_____ Date:_____

Medical Screening – ACSM Medical Screening Questionnaire

___ Do you have any personal history of heart disease?
___ Do you have any personal history of metabolic disease (thyroid, renal, liver)?
___ Have you had diabetes for less than 15 years?
___ Have you had diabetes for 15 years or more?
___ Have you experienced pain or discomfort in your chest apparently due to blood flow deficiency?
___ Any unaccustomed shortness of breath (perhaps during light exercise)?
___ Have you had any problems with dizziness or fainting?
___ Do you have difficulty breathing while standing or sudden breathing problems at night?
___ Do you suffer from ankle oedema (swelling of the ankles)?
___ Have you experienced a rapid throbbing or fluttering of the heart?
___ Have you experienced severe pain in leg muscles during walking?
___ Do you have a known heart murmur?
___ Do you have any family history of cardiac or pulmonary disease prior to age 55?
___ Have you been assessed as hypertensive on at least 2 occasions?
___ Has your serum cholesterol been measured at greater than 5.4mmol/l?
___ Are you a cigarette smoker?
___ Would you characterize your lifestyle as "sedentary"?

Medical History

___ Are you currently being treated for high blood pressure?
If you know your average blood pressure, please enter: _____/_____
Please Check All That Apply.

_ has doctor ever found an abnormal ECG?	_ Limited Range of Motion?	_ Stroke?
	_ Recently Broken Bones?	
_ Abnormal Chest X-Ray?	_ Arthritis?	_ Epilepsy or Seizures?
_ Rheumatic Fever?	_ Bursitis?	_ chronic Headaches or Migraines?
_ Low Blood Pressure?	_ Swollen or Painful Joints?	_ Persistent Fatigue?
_ Asthma?	_ Foot Problems?	_ Stomach Problems?
_ Bronchitis?	_ Knee Problems?	_ Hernia?
_ Emphysema?	_ Back Problems?	_ Anemia?
_ Other Lung Problems?	_ Shoulder Problems?	_ Are You Pregnant?

_ Has a doctor imposed any activity restrictions? If so, please describe:

_____

_____

_____

Family History

Have your mother, father, or siblings suffered from (please select all that apply):

___ Heart attack or surgery prior to age 55
___ Stroke prior to age 50
___ Congenital heart disease or left ventricular hypertrophy
___ High cholesterol
___ Diabetes
___ Obesity
___ Hypertension
___ Osteoporosis
___ Asthma
___ Leukemia or cancer prior to age 60

Medications

Please Select Any Medications You Are Currently Using

_ Diuretics
_ Beta Blockers
_ Vasodilators
_ Alpha Blockers
_ Calcium Channel Blockers
_ Other Cardiovascular
_ NSAIDS/Anti-inflammatories (Motrin, Advil)
_ Cholesterol
_ Diabetes/Insulin
_ Other Drugs (record below).

Please list the specific medications that you currently take:

_____

_____

Emergency Contacts

Please list your general practitioner and person to be contacted in case of emergency

Doctor: _____ Phone: _____

Contact: _____ Phone: _____

Activities and Goals

On average, how many times do you exercise per week? _____

On average, how long do you exercise? _____ minutes

On a scale from 1 to 10, how intense is your typical workout (circle one):

Very Easy **1** **2** **3** **4** **5** **6** **7** **8** **9** **10** Very Intense

For each activity that you participate in, indicate your typical exercise time in minutes per session:

Running/Jogging:	_____	Weight Training:	_____	Skiing/Boarding:	_____
Walking:	_____	Aerobics Classes:	_____	Yoga/Martial Arts:	_____
Stair Climbing:	_____	Swimming:	_____	Other:	_____
Bicycle/Spinning:	_____	Racquet Sports:	_____		

Lifestyle

Are you a cigarette smoker? _____ If so, how many per day? _____
Previously a cigarette smoker? _____ If so, when did you quit? _____
How many years have you smoked or did you smoke before quitting? _____
Do you/did you smoke: cigarettes? cigars? pipe?

Please rate your daily stress levels (select one):

Low	Moderate	High: I enjoy the challenge	High: sometimes difficult to handle	High: often difficult to handle

Do you drink alcoholic beverages? _____
How many units of alcohol do you consume per week: _____ (see Alcohol Units Calculator below)

Alcohol Units Calculator

Type of Drink	Units
1 glass of wine	1
1 pub measure of spirits (Gin, Vodka etc.)	1
1 can of beer	1.5
1 bottle of strong lager	2.5

1 can of strong lager

4

1 bottle of wine

7

1 litre bottle of wine

10

1 bottle of fortified wine (port, sherry etc.)

14

1 bottle of spirits

30

Dietary Habits: Please select all that apply

___ I seldom consume red or high fat meats
___ I pursue a low-fat diet
___ I eat at least 5 servings of fruits/vegetables per day
___ I almost always eat a full, healthy breakfast
___ My diet includes many high-fiber foods
___ I rarely eat sugar of high-fat dessert

Other

Please indicate any other medical conditions or activity restrictions that you may have. It is important that this information be as accurate and complete as possible.

Is any of this information critical to understanding your readiness for exercise? Are there any other restrictions on activity that we should know about?

Thank you for taking the time to complete this questionnaire!

APPENDIX D

Stellenbosch Mood Scale

Die Stellenbosch Gemoedskaal /The Stellenbosch Mood Scale

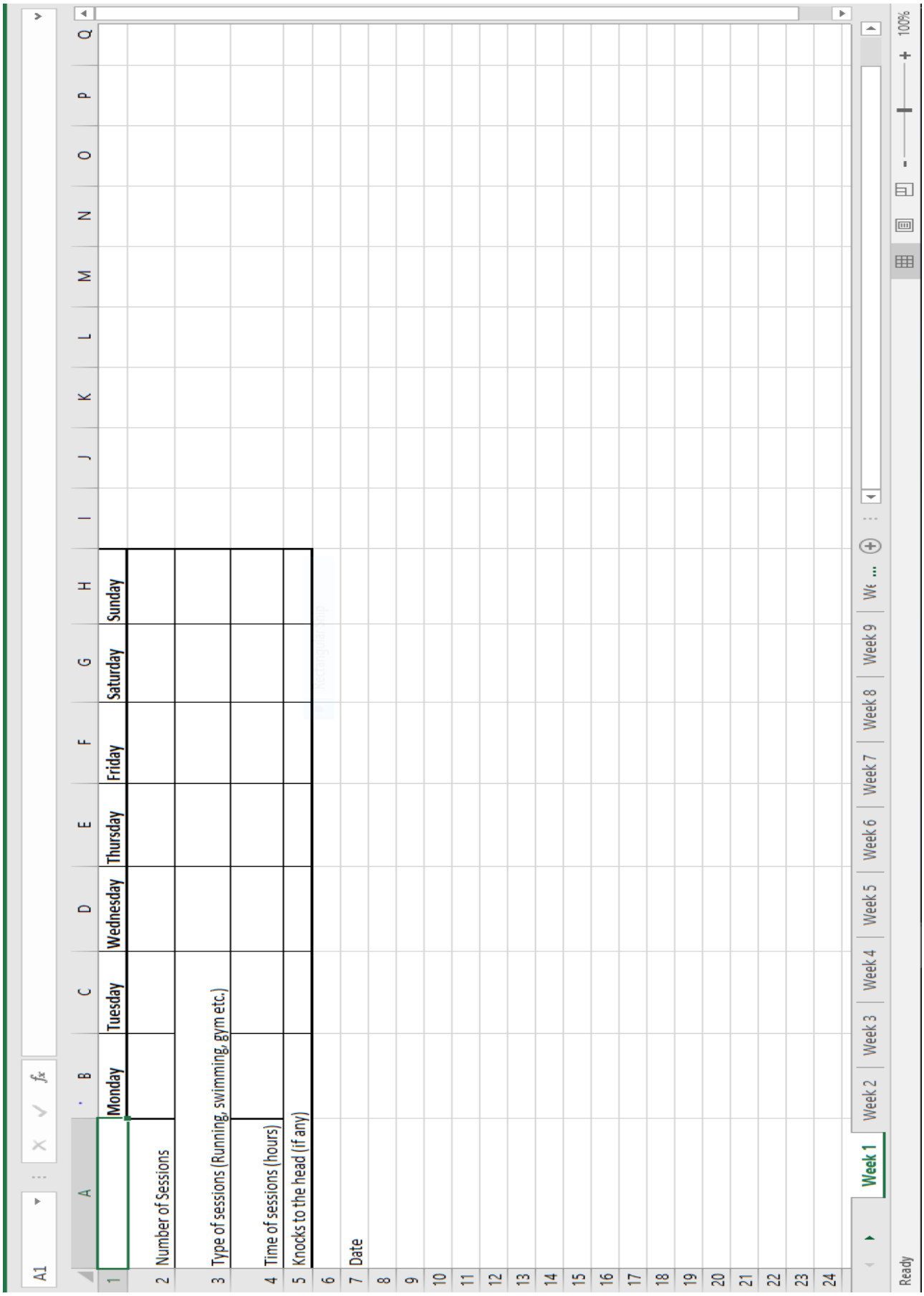
Naam/ Name: Datum /Date:

Hieronder is 'n lys van woorde wat die gevoelens van mense beskryf. Lees asseblief elkeen noukeurig. Omsirkel daarna die antwoord wat die beste beskryf *hoe jy op hierdie oomblik voel.*

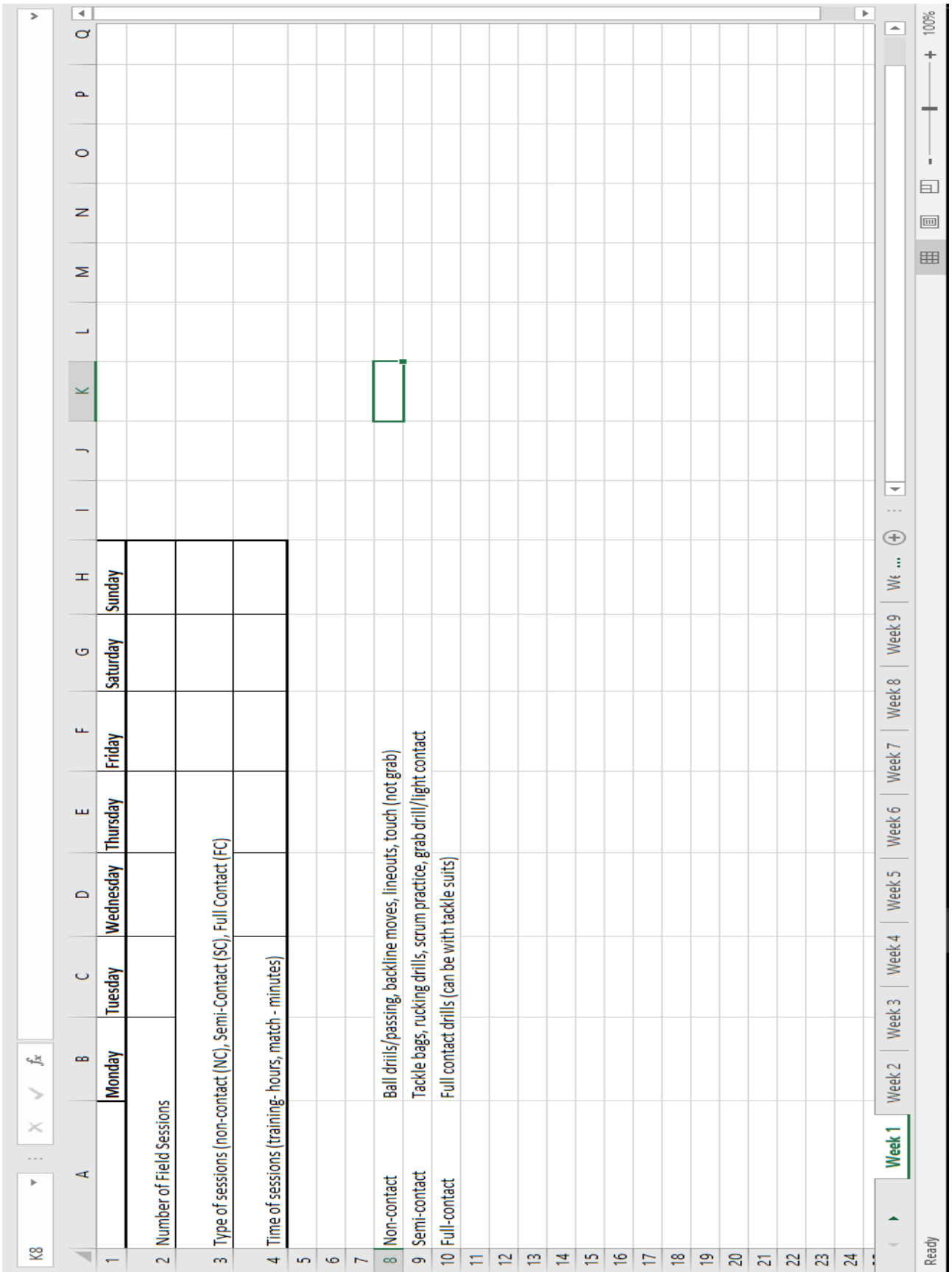
Below is a list of words that describe feelings people have. Please read each one carefully. Then circle the answer that best describes *how you feel right now.*

	Glad nie Not at all	Effens A little	Taamlik Moderately	Baie Quite a bit	Uiters Extremely	
Paniekerig	0	1	2	3	4	Panicky
Lewendig	0	1	2	3	4	Lively
Verward	0	1	2	3	4	Confused
Vermoeid	0	1	2	3	4	Worn out
Neerslagtig	0	1	2	3	4	Depressed
Mismoedig	0	1	2	3	4	Downhearted
Vererg	0	1	2	3	4	Annoyed
Uitgeput	0	1	2	3	4	Exhausted
Deurmekaar	0	1	2	3	4	Mixed up
Vaak	0	1	2	3	4	Sleepy
Verbitterd	0	1	2	3	4	Bitter
Ongelukkig	0	1	2	3	4	Unhappy
Angstig	0	1	2	3	4	Anxious
Bekommerd	0	1	2	3	4	Worried
Energiek	0	1	2	3	4	Energetic
Ellendig	0	1	2	3	4	Miserable
Ontwrig	0	1	2	3	4	Muddled
Senuweeagtig	0	1	2	3	4	Nervous
Kwaad	0	1	2	3	4	Angry
Aktief	0	1	2	3	4	Active
Moeg	0	1	2	3	4	Tired
Humeurig	0	1	2	3	4	Bad tempered
Op en wakker	0	1	2	3	4	Alert
Onseker	0	1	2	3	4	Uncertain

APPENDIX E



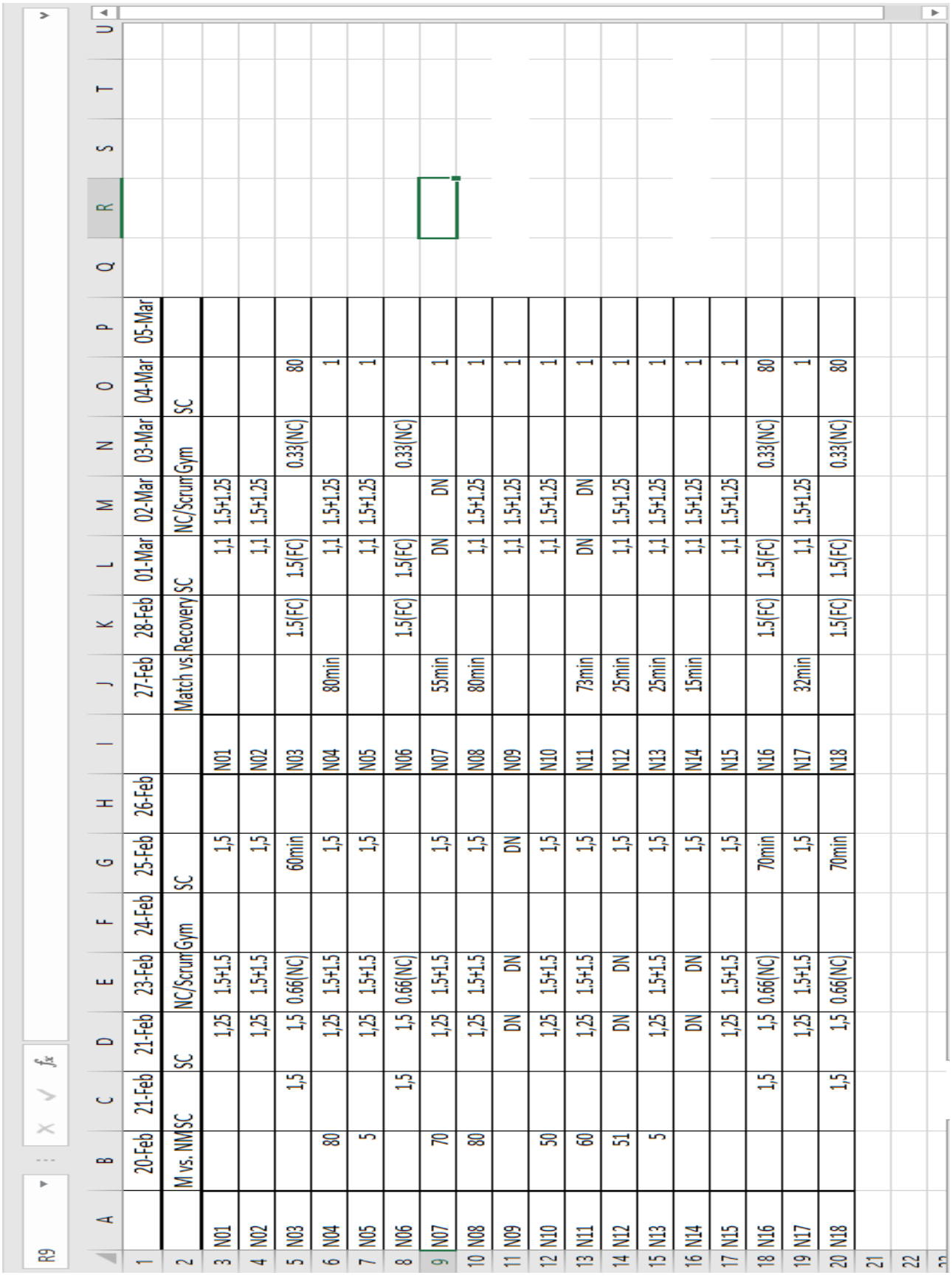
APPENDIX F



	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Number of Field Sessions							
Type of sessions (non-contact (NC), Semi-Contact (SC), Full Contact (FC)							
Time of sessions (training- hours, match - minutes)							
Non-contact	Ball drills/passing, backline moves, lineouts, touch (not grab)						
Semi-contact	Tackle bags, rucking drills, scrum practice, grab drill/light contact						
Full-contact	Full contact drills (can be with tackle suits)						

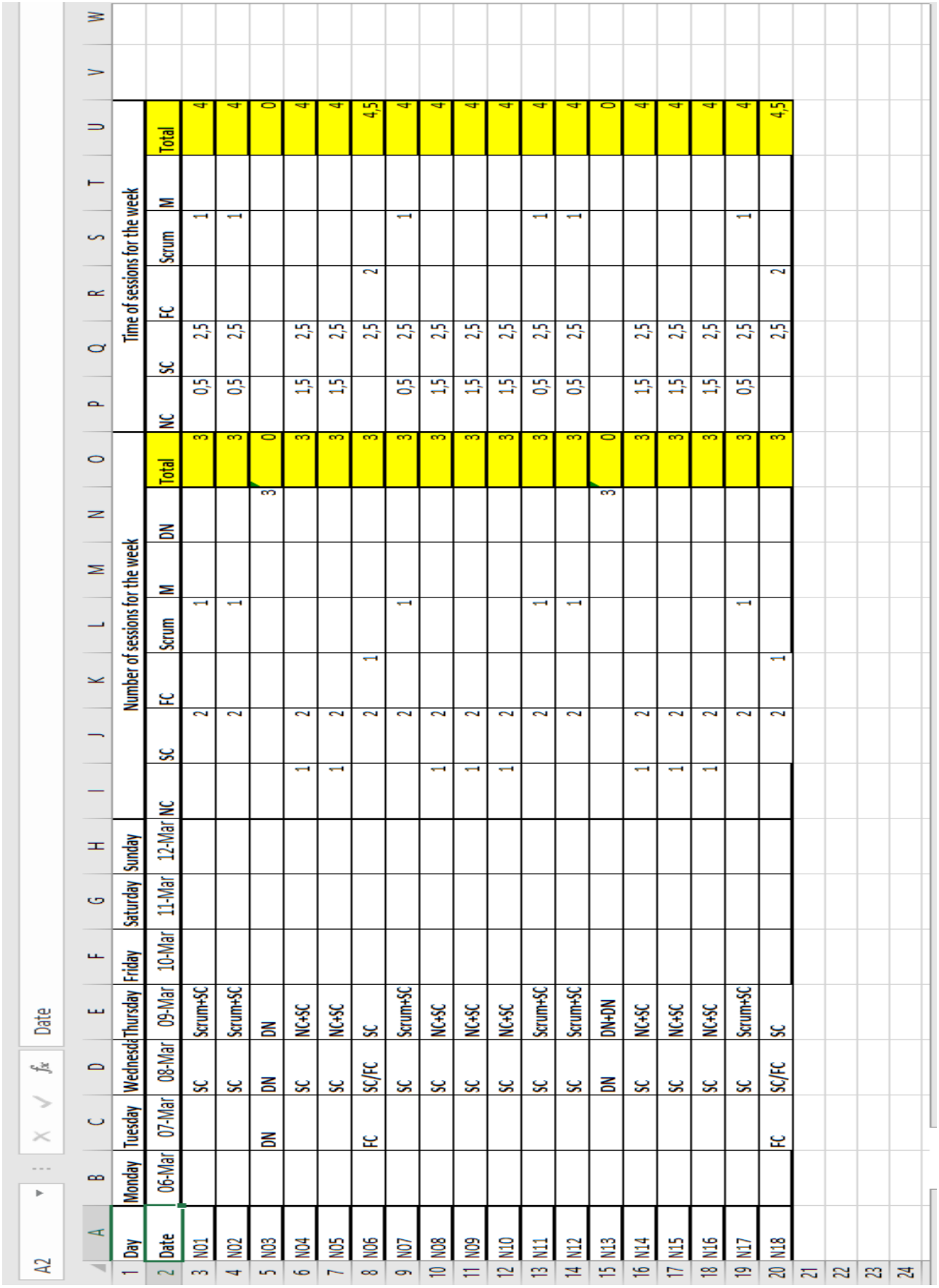
APPENDIX G

1. Daily Log Book



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
1		20-Feb	21-Feb	21-Feb	23-Feb	24-Feb	25-Feb	26-Feb		27-Feb	28-Feb	01-Mar	02-Mar	03-Mar	04-Mar	05-Mar					
2		M vs. NM	SC	SC	NC/Scrum	Gym	SC			Match vs.	Recovery	SC	NC/Scrum	Gym	SC						
3	N01			1,25	1.5+1.5		1,5		N01			1,1	1.5+1.25								
4	N02			1,25	1.5+1.5		1,5		N02			1,1	1.5+1.25								
5	N03		1,5	1,5	0.66(NC)		60min		N03		1.5(FC)	1.5(FC)		0.33(NC)	80						
6	N04	80		1,25	1.5+1.5		1,5		N04	80min		1,1	1.5+1.25		1						
7	N05	5		1,25	1.5+1.5		1,5		N05			1,1	1.5+1.25		1						
8	N06		1,5	1,5	0.66(NC)				N06		1.5(FC)	1.5(FC)		0.33(NC)							
9	N07	70		1,25	1.5+1.5		1,5		N07	55min		DN	DN		1						
10	N08	80		1,25	1.5+1.5		1,5		N08	80min		1,1	1.5+1.25		1						
11	N09			DN	DN		DN		N09			1,1	1.5+1.25		1						
12	N10	50		1,25	1.5+1.5		1,5		N10			1,1	1.5+1.25		1						
13	N11	60		1,25	1.5+1.5		1,5		N11	73min		DN	DN		1						
14	N12	51		DN	DN		1,5		N12	25min		1,1	1.5+1.25		1						
15	N13	5		1,25	1.5+1.5		1,5		N13	25min		1,1	1.5+1.25		1						
16	N14			DN	DN		1,5		N14	15min		1,1	1.5+1.25		1						
17	N15			1,25	1.5+1.5		1,5		N15			1,1	1.5+1.25		1						
18	N16		1,5	1,5	0.66(NC)		70min		N16		1.5(FC)	1.5(FC)		0.33(NC)	80						
19	N17			1,25	1.5+1.5		1,5		N17	32min		1,1	1.5+1.25		1						
20	N18		1,5	1,5	0.66(NC)		70min		N18		1.5(FC)	1.5(FC)		0.33(NC)	80						
21																					
22																					

2. Weekly Summary



Day	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Number of sessions for the week								Time of sessions for the week					
Date	06-Mar	07-Mar	08-Mar	09-Mar	10-Mar	11-Mar	12-Mar	NC	SC	FC	Scrum	M	DN	Total	NC	SC	FC	Scrum	M	Total
N01			SC	Scrum+SC						2		1		3	0,5	2,5		1		4
N02			SC	Scrum+SC						2		1		3	0,5	2,5		1		4
N03		DN	DN	DN									3	0						0
N04			SC	NC+SC					1	2				3	1,5	2,5				4
N05			SC	NC+SC					1	2				3	1,5	2,5				4
N06		FC	SC/FC	SC						2	1			3		2,5	2			4,5
N07			SC	Scrum+SC						2		1		3	0,5	2,5		1		4
N08			SC	NC+SC					1	2				3	1,5	2,5				4
N09			SC	NC+SC					1	2				3	1,5	2,5				4
N10			SC	NC+SC					1	2				3	1,5	2,5				4
N11			SC	Scrum+SC						2		1		3	0,5	2,5		1		4
N12			SC	Scrum+SC						2		1		3	0,5	2,5		1		4
N13			DN	DN+DN									3	0						0
N14			SC	NC+SC					1	2				3	1,5	2,5				4
N15			SC	NC+SC					1	2				3	1,5	2,5				4
N16			SC	NC+SC					1	2				3	1,5	2,5				4
N17			SC	Scrum+SC						2		1		3	0,5	2,5		1		4
N18		FC	SC/FC	SC						2	1			3		2,5	2			4,5

APPENDIX H

Table H.1. CNS Vital Signs Test Scores of the Rugby participants. Results are presented as mean ± SD.

Cognitive Test	Pre mean ± SD	Post mean ± SD	Mean Diff. [95% CI]	ES [95% CI]	Qualitative Outcome	P-Value
Finger Tap Test Right	68,4 ± 9,20	69,4 ± 7,32	1,06 [-4,94 ; 7,07]	0,13 [-0,57 ; 0,82]	N	> 0,05
Finger Tap Test Left	58,6 ± 6,13	60,4 ± 5,38	1,75 [-2,41 ; 5,91]	0,30 [-0,40 ; 0,99]	S	> 0,05
SDC Correct Responses	59,9 ± 8,94	65,1 ± 10,49	5,19 [-1,85 ; 12,23]	0,53 [-0,19 ; 1,22]	M	> 0,05
SDC Errors#	1,6 ± 1,67	2 ± 2,16	0,38 [-1,02 ; 1,77]	0,19 [-0,51 ; 0,88]	N	> 0,05
Stroop 1 Reaction Time (ms)#	260,9 ± 24,21	261,6 ± 23,69	0,69 [-16,61 ; 17,98]	0,03 [-0,67 ; 0,72]	N	> 0,05
Stroop2 Reaction Time (ms)#	564,6 ± 68,48	573,2 ± 98,74	8,63 [-52,73 ; 69,98]	0,10 [-0,59 ; 0,79]	N	> 0,05
Stroop 3 Reaction Time (ms) #	686 ± 131,38	680,1 ± 108,67	-5,94 [-92,99 ; 81,11]	-0,05 [-0,74 ; 0,65]	N	> 0,05
Stroop 2 Correct Responses	12 ± 0,00	12 ± 0,00	0,00 [0,00 ; 0,00]	0,00 [0,00 ; 0,00]	N	> 0,05
Stroop 2 Errors#	0,6 ± 0,81	0,4 ± 0,62	-0,25 [-0,77 ; 0,27]	-0,35 [-1,04 ; 0,36]	S	> 0,05
Stroop 3 Correct Responses	23,5 ± 1,75	23,9 ± 0,25	0,44 [-0,47 ; 1,34]	0,35 [-0,36 ; 1,04]	S	> 0,05
Stroop 3 Errors#	2,9 ± 2,13	1,8 ± 1,53	-1,13 [-2,46 ; 0,21]	-0,61 [-1,30 ; 0,12]	M	> 0,05
SAT Correct Responses	55,5 ± 6,10	57,3 ± 7,21	1,81 [-3,01 ; 6,63]	0,27 [-0,43 ; 0,96]	S	> 0,05
SAT Errors#	5,8 ± 2,35	5,9 ± 3,40	0,13 [-1,99 ; 2,24]	0,04 [-0,65 ; 0,73]	N	> 0,05
SAT Reaction Time (ms)#	996,3 ± 156,48	951,4 ± 157,30	-44,88 [-158,16 ; 68,41]	-0,29 [-0,98 ; 0,42]	S	> 0,05
CPT Correct Responses	39,9 ± 0,34	39,8 ± 0,54	-0,06 [-0,39 ; 0,27]	-0,14 [-0,83 ; 0,56]	N	> 0,05
CPT Errors#	0,6 ± 1,02	1,1 ± 1,26	0,50 [-0,33 ; 1,33]	0,44 [-0,28 ; 1,13]	S	> 0,05
CPT Reaction Time (ms)#	394,3 ± 29,99	393,9 ± 25,75	-1,06 [-21,24 ; 19,12]	-0,04 [-0,73 ; 0,66]	N	> 0,05

Lower score indicates better performance. * Significant differences. SDC, Symbol digit coding test; SAT, Shifting attentions test; CPT, continuous performance test. N, No effect; S, Small effect; M, Medium effect; L, Large effect; VL, Very large effect.

Table H.2. CNS Vital Signs Test Scores of the Control participants. Results are presented as mean ± SD.

Cognitive Test	Pre mean ± SD	Post mean ± SD	Mean Diff. [95% CI]	ES [95% CI]	Qualitative Outcome	P-Value
Finger Tap Test Right	65,7 ± 9,20	63,8 ± 6,64	-1,92 [- 8,42 ; 4,57]	-0,24 [-1,00 ; 0,54]	S	> 0,05
Finger Tap Test Left	56,2 ± 7,00	56,2 ± 7,64	-0,08 [-6,01 ; 5,85]	-0,01 [-0,78 ; 0,76]	N	> 0,05
SDC Correct Responses	67,4 ± 7,26	69,8 ± 9,05	2,38 [-4,26 ; 9,03]	0,29 [-0,49 ; 1,05]	S	> 0,05
SDC Errors#	1,7 ± 2,14	2,8 ± 1,42	1,08 [-0,39 ; 2,55]	0,59 [-1,36 ; 0,21]	M	> 0,05
Stroop 1 Reaction Time (ms)#	253,4 ± 11,25	251,1 ± 11,16	-2,33 [-11,82 ; 7,16]	-0,21 [-1,00 ; 0,60]	S	> 0,05
Stroop2 Reaction Time (ms)#	528,1 ± 42,94	542,3 ± 33,71	14,17 [-18,51 ; 46,85]	0,37 [-0,45 ; 1,16]	S	> 0,05
Stroop 3 Reaction Time (ms)#	620 ± 74,26	615,7 ± 50,11	-4,33 [-57,97 ; 49,30]	-0,07 [-0,87 ; 0,73]	N	> 0,05
Stroop 2 Correct Responses	12 ± 0,00	12 ± 0,00	0 [0,00 ; 0,00]	0,00 [0,00 ; 0,00]	N	> 0,05
Stroop 2 Errors*	0,3 ± 0,49	0,6 ± 0,67	0,25 [-0,25 ; 0,75]	0,43 [-0,40 ; 1,22]	S	> 0,05
Stroop 3 Correct Responses	24 ± 0,00	24 ± 0,00	0 [0,00 ; 0,00]	0,00 [0,00 ; 0,00]	N	> 0,05
Stroop 3 Errors*	1,9 ±1,00	2,8 ± 1,76	0,83 [-0,38 ; 2,05]	0,58 [-0,25 ; 1,38]	M	> 0,05
SAT Correct Responses	56,8 ± 6,52	61,6 ± 6,38	4,85 [-0,38 ; 10,07]	0,75 [-0,07 ; 1,52]	M	> 0,05
SAT Errors*	6 ± 3,24	4,2 ± 1,17	-1,77 [-3,74 ; 0,20]	-0,73 [-1,50 ; 0,09]	M	> 0,05
SAT Reaction Time* (ms)	951,6 ± 108,50	885,8 ± 125,32	-65,38 [-160,27 ; 29,50]	-0,56 [-1,32 ; 0,24]	M	> 0,05
CPT Correct Responses	39,9 ± 0,28	39,9 ± 0,28	0,00 [-0,22 ; 0,22]	0,00 [-0,77 ; 0,77]	N	> 0,05
CPT Errors*	0,1 ± 0,38	0,3 ± 0,63	0,15 [- 0,27 ; 0,57]	0,30 [-0,49 ; 1,06]	S	> 0,05
CPT Reaction Time* (ms)	376,7 ± 22,98	380,9 ± 19,75	4,23 [-13,11 ; 21,57]	0,20 [-0,58 ; 0,96]	S	> 0,05

Lower score indicates better performance. * Significant differences. SDC, Symbol digit coding test; SAT, Shifting attentions test; CPT, continuous performance test. N, No effect; S, Small effect; M, Medium effect; L, Large effect; VL, Very large effect.

Table H.3. Between-group differences for Change in CNS Vital Signs test scores for Rugby and Control.

Cognitive Test	Rugby mean ± SD	Control mean ± SD	Mean Diff. [95% CI]	ES [95% CI]	Qualitative Outcome	P-Value
Finger Tap Test Right	1,06 ± 4,89	-1,92 ± 4,82	2,99 [-0,74 ; 6,71]	0,61 [-0,15 ; 1,34]	M	> 0,05
Finger Tap Test Left	1,75 ± 6,42	-0,08 ± 5,30	1,83 [-2,73 ; 6,39]	0,31 [-0,44 ; 1,03]	S	> 0,05
SDC Correct Responses	5,19 ± 7,67	2,38 ± 9,52	2,80 [-3,74 ; 9,35]	0,33 [-0,42 ; 1,06]	S	> 0,05
SDC Errors#	0,38 ± 2,99	1,08 ± 1,66	-0,70 [-2,61 ; 1,20]	-0,28 [-1,01 ; -,46]	S	> 0,05
Stroop 1 Reaction Time (ms)#	0,69 ± 22,58	-2,33 ± 11,64	3,02 [11,69 ; 17,74]	0,16 [-0,59 ; 0,91]	N	> 0,05
Stroop2 Reaction Time (ms)#	8,63 ± 78,36	14,17 ± 23,30	-5,54 [-53,75 ; 42,67]	-0,09 [-0,84 ; 0,66]	N	> 0,05
Stroop 3 Reaction Time (ms)#	-5,94 ± 77,81	-4,33 ± 74,30	-1,60 [-61,53 ; 58,32]	-0,02 [-0,77 ; 0,73]	N	> 0,05
Stroop 2 Correct Responses	0,00 ± 0,00	0,00 ± 0,00	0,00 [0,00 ; 0,00]	0,00 [0,00 ; 0,00]	N	> 0,05
Stroop 2 Errors#	-0,25 ± 0,86	0,25 ± 0,75	-0,50 [-1,14 ; 0,14]	-0,61 [-1,36 ; 0,17]	M	> 0,05
Stroop 3 Correct Responses	0,44 ± 1,75	0,00 ± 0,00	0,44 [-0,61 ; 1,48]	0,33 [-0,43 ; 1,07]	S	> 0,05
Stroop 3 Errors#	-1,13 ± 2,36	0,83 ± 1,64	-1,96 [-3,60 ; -0,32]	-0,94 [-1,70 ; -0,12]	L	0,02*
SAT Correct Responses	1,81 ± 4,13	4,85 ± 7,08	-3,03 [-7,35 ; 1,29]	-0,54 [-1,27 ; 0,22]	M	> 0,05
SAT Errors#	0,13 ± 3,01	-1,77 ± 3,70	1,89 [-0,66 ; 4,45]	0,57 [-0,19 ; 1,30]	M	> 0,05
SAT Reaction Time (ms)#	-44,88 ± 83,77	-65,38 ± 87,85	20,51 [-0,45 ; 0,33]	0,24 [-0,50 ; 0,97]	S	> 0,05
CPT Correct Responses	-0,06 ± 0,57	0,00 ± 0,41	-0,06 [-0,45 ; 0,33]	-0,12 [-0,85 ; 0,61]	N	> 0,05
CPT Errors#	0,50 ± 1,32	0,15 ± 0,69	0,35 [-0,48 ; 1,18]	0,32 [-0,43 ; 1,05]	S	> 0,05
CPT Reaction Time (ms)#	-1,06 ± 30,59	4,23 ± 18,16	-5,29 [-25,07 ; 14,48]	-0,21 [-0,93 ; 0,53]	S	> 0,05

Lower score indicates better performance. * Significant differences. SDC, Symbol digit coding test; SAT, Shifting attentions test; CPT, continuous performance test. N, No effect; S, Small effect; M, Medium effect; L, Large effect; VL, Very large effect.