A HOLISTIC INVESTIGATION OF AMATEUR BATTERS PERFORMANCE RESPONSES TO A CENTURY PROTOCOL: A FOCUSED COGNITIVE PERSPECTIVE

BY

DAVID GOBLE

DISSERTATION

Submitted in fulfilment of the requirements for the Degree of

Doctor of Philosophy

Department of Human Kinetics and Ergonomics

Rhodes University, 2016

Grahamstown, South Africa

ABSTRACT

No cognitive study has implemented an exercise modality that requires both physical effort and cognitive control, therefore, the effects of such exercise are unknown. Additionally, no studies have investigated how prolonged batting impacts cognitive functioning nor how physical responses and cognitive functioning are related while batting. At intensities of 60-70 percent heart rate maximum, acute and prolonged bouts of physical activity have been shown to improve cognitive functioning. At higher intensities, the beneficial effects are minimal and in some cases performance is impaired. Therefore, the aim of this investigation was to determine how prolonged intermittent batting (a task that requires high muscular and cardiovascular loads but also continuous cognitive control) affects cognitive, physiological, physical and biophysical responses in amateur batters. Further aims included to test the reliability of the method employed in assessing these responses.

To answer this question, the investigation was separated into three studies: *phase 1* (a large-scale pilot) and *phase 2* and *3* (a repeated measures test-retest hypothesis). In each phase, batters completed the 30 over BATEX simulation, which replicated the demands of scoring a one-day international century. To establish physiological, physical and perceptual strain; heart rate, sprint times and perceived exertion data were collected each over. Changes in body mass over time were compared to determine the effects of fluid loss on cognitive performance. Before, during and after the simulation, psychomotor function, visual attention, working memory, visual learning and memory as well as executive functions were assessed (CogState brief test battery). During cognitive assessments, heart rate and heart rate variability parameters were sampled so that autonomic modulation of the heart could be determined. The methodological differences between *phase 1* and *phase 2* and *3*, were (respectively); the frequency of cognitive assessments (five vs. three), the samples used (15 schoolboy vs. 16 academy batters), hydration protocols (250ml of Energade vs. water *ad libitum*) and a singular change in a physical dependent variable (batting accuracy vs. vertical jump).

In schoolboy and academy batters, the prolonged batting simulation placed significant strain on the cardiovascular and muscular subsystems; increasing heart rate ($p<0.01$), decreasing body mass ($p<0.01$) and deteriorating sprint performance ($p<0.01$) over time. In each sample, batters' perceived exertion increased significantly ($p<0.01$) and exertion was highest in the final over of the protocol. Interestingly, the changes in cardiovascular and muscular responses were larger in schoolboy batters.

While the cognitive performance decrements over time were not significant in academy batters ($p>0.05$; $d<0.2$), the magnitude of impairment in psychomotor function ($p>0.05$; $d = 0.37$), visual attention ($p>0.05$; $d = 0.56$), working memory ($p>0.05$; $d = 0.61$) and executive function ($p>0.05$; $d = 0.58$) was larger in schoolboy batters. In both samples, the simulation altered the modulation of heart rate significantly. Heart rate variability decreased linearly with time spent batting ($p<0.01$; $d>0.8$). During cognitive assessments, heart rate variability increased with time-on-task, where responses were significantly higher ($p<0.05$) in the last task of the battery compared to the first. Importantly, the results of the *retest* phase were the same as in the *test* phase and only two *condition effects* were observed; (i) heart rate (*retest* lower: $p<0.04$;$d = 0.39$), (ii) body mass (*retest* lower: $p<0.03$;$d = 0.09$). A task-related *condition effect* in heart rate variability (PNN30) was also observed (*retest* higher: $p<0.03$; d = not calculated). Resultantly, the *test-retest* reliability of *phase 2* and *3* was high.

The results indicate that prolonged intermittent batting at an intensity of 64-77 $\%HR_{max}$ impaired cognitive functioning in amateur batters. However, the cardiovascular and muscular strain induced by prolonged intermittent batting and its effects on cognitive functioning are mediated by intrinsic and extrinsic factors (age, training status, playing experience and hydration). Therefore, while prolonged batting has similar effects on cognitive functioning as acute bouts of physical activity, they do not share the same relationship. The author hypothesises that the continuous cognitive component inherent in prolonged batting mitigates the beneficial effects of physical activity, as demonstrated previously. Future research is needed to elucidate this relationship. Additionally, player experience affects the way in which batters regulate performance while batting; which also affects the rate of and magnitude of impairment during batting. Finally, the methodological limitations of this study provide direction for future research into batting.

ACKNOWLEDGEMENTS

I would like to thank Professor Candice Christie for her mentorship and trust over the last four years. You allowed me to work independently yet taught me valuable skills during the course of this study. Thank you for all your efforts, ‘on and off the field’, that a typical supervisor does not consider. Your patronage on this journey has been invaluable and the sacrifices you made will never be forgotten. Thank you!

Samantha Bezuidenhout, without your care and love I am not sure that I would have made it to this point. Thank you for your never-failing support and for being my confidant over the last 6 years.

Special thanks must go to my family; Clive, Jennifer, Michael, Tarryn, Jessica, Megan and Paige for their constant love, support and encouragement through the course of this study, but also in everything I do. I love you all and I remain forever grateful to you all. Thank you to Peta Myers for your guidance along the way and for providing me a home away from home.

I would like to thank the members of staff and my colleagues from the Department of Human Kinetics and Ergonomics for their input into this study. Special thanks to Jonathan Davy for his advice and guidance throughout my dissertation. Many thanks too to Robert Jones and Lee Pote for their friendship and backing.

I would also like to thank Mr Zolani Gubuza and the TUKS ASSUPOL cricket academy. Your professional conduct, help and guidance during my time at the centre of excellence was instrumental in my research.

I would like to thank the schools and coaches for your assistance in participant recruitment, particularly Kingswood College and King Edward School. To Carl Bradfield, Murray Ranger and Gordon Matheson, without your help experimentation would not have been possible, thank you.

Lastly, thank you to my participants, for their willingness to participate and for never letting me down, without you this research could not have been done.

DISSERTATION RESEARCH OUTPUTS

Peer Reviewed Publications

Goble D and Christie CJ. (2016). Cognitive, physical and physiological responses of school boy cricketers to a 30-over batting simulation. *Journal of Sports Sciences,* 0: 1–7. Available: http://dx.doi.org/10.1080/02640414.2016.1211731.

Goble D and Christie CJ (under review). Investigating the information processing capabilities and performance responses of academy cricket batters: implications of prolonged batting. Journal of Sports Sciences.

Conference Publications

Goble D and Christie CJ. *The effects of a 30 over simulated batting protocol on cognitive performance: A preliminary investigation.* 5th World Congress of Science and Medicine in Cricket. Sydney, Australia, 23-27 March 2015.

Goble D and Christie CJ. *An investigation into the cognitive dynamics of batting: measurement of information processing in amateur cricket batsmen.* 16th Biennial Congress of S.A.S.M.A, Sandton Convention Centre, October 2015.

TABLE OF CONTENTS

CHAPTER I

CHAPTER II

CHAPTER III

CHAPTER IV

CHAPTER V

CHAPTER VI

CHAPTER VII

CHAPTER VIII

LIST OF TABLES

TABLE **PAGE**

LIST OF FIGURES

CHAPTER I - INTRODUCTION

1.1 In the Head of a Batter

From the roars and boos of the crowd to fall of a wicket, each batter as they walk out to bat, will be overwhelmed by an abundance of stimuli. As batters set foot onto the field and approach the pitch, the brain continually needs to sift and process information. The crowd is often the first stimulus that batters perceive where home and away games play an integral role in feelings of confidence or intimidation. Thereafter, and with the intention of intimidation, the eleven opposition fielders often try to talk the batter out of his comfort zone. The intimidation increases as the batter prepares to face the first delivery. At this stage the number of stimuli that need processing increase exponentially and before the batter can intercept the ball, several essential information processing sequences are completed. The ability to do this efficiently, while reducing errors, is fundamental to batting success.

First, the batter must observe the field and fielding positions for potential ‘traps’ that have been set by the opposition. They must then select certain areas in the field that suit their strengths and scoring areas. Second and while cognisant of these areas, the batter must observe certain gestures of the bowler as they approach their delivery stride (point of ball release). These include, the speed of approach, the angle of approach, the position of the ball in the bowler’s hand and the height at which the ball is released. This pre-delivery information allows the batter to make anticipatory movements in the preparation of shot selection. Therefore, as early as pre-ball release, the information processing system is hard at work.

At the point of ball release, the temporal constraints placed on batters are severe. When facing a fast bowler (120-150 $km.h^{-1}$) batters have approximately 425-530 ms from ball release to arrival at the bat. Furthermore, once the ball has pitched the remaining time to react is roughly 180-200 ms (Land & McLeod, 2000). In this time batters must detect and track the ball, interpret the visual information obtained (line and length of the delivery and late deviations in ball flight), make a decision to play or leave the ball and then program the motor system based on this decision. When a shot is executed the batter must then reassess the situation. Here, the batter must determine the direction of the ball and whether or not the ball has entered a ‘gap’ in the field. The batter must then decide whether or not there is time to complete a run. In the event that a run is 'on' a new motor programming sequence must be initiated that will start the process of running (McArdle, Katch, & Katch, 2006). While running, the batter needs to continually observe and update the ball position, relative to the fielders, and decide whether a second or perhaps a third run is possible and if so, once again, the neuromuscular system must be reprogrammed. While this is only one delivery, batters repeat these processes hundreds of times when scoring a century. Additionally, batters also need to complete runs for their partners. This necessitates similar information processing sequences and as a result the batters mind is never at rest.

Where this example is examined from a fast bowling standpoint, batters are also required to intercept balls that move prodigiously in the air (swing bowling) or off the pitch (seam/spin bowling). Despite slower ball speeds, swing and spin bowling require heightened selective attention as the deviations in flight or movement often occur late in the delivery (just before the ball arrives at the batter). In these examples, early detection of pre-delivery information is crucial, as this often indicates to the batter what type of delivery could be bowled.

While batting is a physically demanding task (Petersen, Pyne, Dawson, Portus & Kellett, 2010) its neurobiological basis is poorly understood. From the above information it is evident that batting is cognitively demanding and that successful batting requires the following traits; vigilance (filtering important from non-important stimuli), fast response times that facilitate accurate and rapid decision making (shot selection and execution), spatial awareness (shot execution and running between the wickets) and efficient executive functioning (executive control in each delivery). Batting also requires effective retrieval of information from short-term and long-term memory to allow decisions to be made and the correct shot selected. Efficient information processing is often the difference between professional and amateur batters, where the ability to isolate attention toward task-relevant information is paramount (Müller, Abernethy, & Farrow, 2006).

1.2 Research Rationale

Cricket is characterised by its highly dynamic intermittent nature where often the type of match being played dictates player demands. This is especially true for batting, where the role of each batter is controlled by the duration of the innings and the current game situation. This ever-changing environment combined with the intermittent nature of batting, make assessments of match-based demands difficult (Christie, Todd, & King, 2008). Further complicating assessment, are the differing match intensities of limited overs (One-Day Internationals [50 overs/inning] and Twenty20's [20 overs/inning]) and Test match cricket (90 overs/day over five days). The seasonal structure, intensity of competition and the unpredictability of match performance all contribute to difficulties in replicating match play in a laboratory (Christie et al., 2008). As a result, batting research is limited.

Limited overs cricket is generally characterised by faster run-rates (runs scored/over), greater distance covered and higher scoring innings' (Petersen et al., 2010), this is because players are likely to accumulate runs more quickly to achieve higher run rates. In contrast, the duration spent 'at the crease' by each batter in Test cricket tends to be lengthier and run rates lower (Petersen et al., 2010). Petersen and colleagues go further to state that, when compared to 20-over game formats, the work-to-recovery ratio is twice as long in Test matches and a third longer in 50-over matches. Limited overs cricket, therefore, encompasses a high-intensity intermittent activity profile, whereas Test cricket is characterised by an intermittent-endurance activity profile.

In all formats, cricket requires physical fitness to withstand the intensities and durations of competition (Johnstone & Ford, 2010). Much like any other sport, as duration and intensity of activity increases, so does the need for physical fitness. A lack of consensus of the physical demands required in batting, necessitates research into the physical, physiological and performance demands of batting. Noakes & Durandt (2000), suggest that when scoring 100 runs in a 50-over match, a batter runs approximately 3.2 km between the wickets in roughly 8.2 min (average speed of 24 km.h^{-1}). Furthermore, the batter decelerates their body mass a minimum of 110 times when competing this distance. The movement characteristics of running between the wickets are: maximally accelerating the body mass over 17.68 m, reducing sprint speed (deceleration), lowering of the body position, stretching and lunging, a 180° turn and accelerating away. When conducted repeatedly this movement pattern is extremely taxing on the body, specifically the lower limb musculature (Sheppard, 2011; Christie, Sheppard, Goble, Pote & Noakes, 2016). To understand why fatigue occurs, the workloads associated with batting must be understood.

Movement studies indicate that in practice and competition, batters cover long distances at various speeds and intensities (walking, jogging and sprinting) and that these strain both the muscular and cardiovascular subsystems (Petersen, Pyne, Portus & Dawson, 2009; Petersen et al., 2010; Petersen, Pyne, Portus & Dawson, 2011; Vickery, Dascombe, Duffield, Kellett & Portus, 2013a, 2013b; Vickery, Dascombe, Duffield, 2014). It is estimated that when batting for 20, 50 and 90 overs, batters complete 3.5 ± 0.2 km, 8.7 ± 0.6 km, and 13.0 ± 2.0 km during each innings (Petersen et al., 2010). These distances have large implications on running performance when batting for prolonged periods. Each time the batter sets off to run, the preceding acceleratory phase of running, would need to be followed by a deceleratory phase. Relatedly, Petersen and colleagues data indicate that batters would need to decelerate the body mass approximately 197, 492 and 735 times, in each respective innings. These decelerations are proposed to increase the eccentric demands of the lower limbs, and when done repeatedly these promote irregular neuromuscular fatigue (Noakes & Durandt, 2000). Fatigue of this nature is said to induce performance reduction where recovery from this state requires substantial time (Nicol, Komi, Marconnet, 1991). In both short duration and prolonged batting periods, fatigue induced through repeated eccentric muscle actions have caused reductions in sprint times, impaired neuromuscular function (decreased peak torque and maximal power) and reduced batting accuracy (good bat-ball contacts) (Christie, 2008; Houghton, Dawson, Rubemson & Tobin, 2011; Lockie, Jeffriess & Callaghan, 2012; Penn & Spratford, 2012; Pote & Christie, 2015). In consideration of competition, these performance reductions can lead to the loss of a wicket, and if done repeatedly these could change the course of a team's innings and the match outcome.

Research investigating the physiological responses of limited overs batting, have found that heart rate fluctuates between 120 and 160 bt.min^{-1} (Christie et al., 2008; Petersen et al., 2010; Houghton, Dawson, Rubenson, 2011; Houghton et al., 2011; Vickery et al., 2013a, 2013b; Christie & Pote, 2014; Vickery et al., 2014; Pote & Christie, 2015). The rate of increase is, however, dependent on the match format and intensity and the level of experience of the player (Petersen et al., 2010; Houghton et al., 2011a; Vickery et al., 2013a, 2013b, 2014). These findings suggest that batting is physiologically demanding, contradicting findings in early research (Noakes & Durandt, 2000; Stretch, Bartlett, & Davids, 2000). Furthermore, short duration batting studies have reported mean oxygen uptakes between 26.7 ± 1.0 - 26.7 ± 3.9 $mlO_2.kg^{-1}.min^{-1}$ (2538 – 2776 $kj.h^{-1}$) (Christie et al., 2008; Christie & Pote, 2014), whereas, prolonged batting (30 overs), has shown higher rates of consumption - 36.65 ± 6.47 $mlO_2.kg^{-1}.min^{-1}$ (Pote, 2013). What is apparent is while the oxygen demand of batters is high, this demand is also intensity- and duration dependent. What is lacking in cricket research is a definitive understanding of oxygen utilization during batting.

Despite its strenuous physical demands, cricket is a game that also requires players to be mentally astute, demanding high levels of selective attention with correct and rapid decision-making processes (Neave et al., 2004; Woolmer, Noakes, & Moffett, 2008). To date, only one cricket-related study has assessed cognition after batting (Neave, Emmett, Moss, Ayton, Scholey, Wesnes, 2004). However, the duration of this protocol was only eight overs and the focus of the study was to determine the impact of helmet use on cognitive functioning. Neave and colleagues found that attention, vigilance and response times were marginally impaired when wearing a helmet. By contrast, no impairments were found in the no-helmet condition. This then suggests that the impairments recorded were due to the addition of the helmet, and not the bout of exercise.

Acute bouts (20-40 min) of constant workload and intermittent exercise are associated with facilitative effects on cognitive functioning (Chang, Labban, Gapin & Etnier, 2012). However, the magnitude of benefit correlates with the following moderators (Tomporowski & Ellis, 1986; Tomporowski, 2003 Lambourne & Tomporowski, 2010; Smith, Blumenthal, Hoffman, Cooper, Strauman et al., 2010; McMorris, Sproule, Turner & Hale, 2011 Chang et al., 2012);

(i) the nature and duration of exercise,
(ii) the activity level and the skill level of the participant,
(iii) the type of cognitive tasks used to assess performance,
(iv) the time of day at which assessment takes place, and
(v) when assessment takes place, during, immediately after exercise or following post-exercise rest.

Importantly, all of these studies (to the authors knowledge) have investigated the effects of purely physical activity, where the exercise modality does not contain added cognitive components (like batting). Additionally, none of these studies have investigated physical activity for longer than 100 min. The effects of activity of this nature are, therefore, unknown.

There is neither data pertaining to the cognitive requirements of batters, nor the associated demands of competition. There is also no data regarding the implications of cognitive fatigue in batters. This paucity is possibly due to the intermittent nature of batting and/or the dynamic environment in which it is performed and/or the lack of understanding into competition demands. Moreover it could be that the methods available for assessment are too time-consuming and may interrupt competition and training. In addition, most of the test batteries designed are catered for clinical practice and not for sports-related assessment, resultantly these lack sport specificity. Evidently, there is a need to complete further research to quantify the cognitive demands of batting and to establish the relationship between physical fatigue and cognitive functioning.

1.3 Research Problem

Although some research has been carried out on batting performance, there are no empirical investigations into the cognitive demands of batting, and the associated effects of fatigue on information processing. What previous research has established is that both short (± seven-over protocols) and long duration innings' (30-over simulations) impose substantial demand on a batter's physiological and muscular systems. Further, it is contended that the increasing physical demands, without appropriate rest, induce reductions in muscular and physical performance. While physical fitness is imperative for batters, successful batting is underpinned by heightened selective attention, efficient decision-making and the minimisation of errors. This is especially true given the increasing seasonal demands placed on batters. What is not yet clear is what the effects of increasing physical demand on cognitive functioning are. Research shows that acute exercise at approximately 60-70% of age-predicted heart rate maximum has facilitative effects on cognition. The effects on prolonged cognitively-demanding activity are yet to be discovered. It is, therefore, imperative to understand how the demands of prolonged batting affect batting performance on a physical, physiological, perceptual and cognitive level. To date, no study has examined batting performance from this holistic perspective.

1.4 Aims and Objectives

The current investigation aims to determine (in amateur batters of schoolboy and academy status) how the physical demands of a prolonged intermittent batting simulation affect cardiovascular, muscular, physical and cognitive performance. Further, through a test-retest hypothesis, to determine if the responses measured are consistent between experimental sessions.

To address these aims, the objectives of the investigation are;

(i) to monitor and establish the degree of cardiovascular and muscular strain imposed by a 30-over intermittent batting simulation,
(ii) to assess psychomotor function, visual attention and vigilance, attention and working memory, visual learning and memory as well as executive functions in batters before, during and post-simulation,
(iii) to measure the degree of change in these cognitive domains,
(iv) to quantify the physical performance of batters in a prolonged setting, and
(v) to determine the reliability of the associated protocol in assessing these variables.

1.5 Research Question and Hypothesis

The experimentation will seek to answer the following question: Does prolonged intermittent batting activity and the subsequent cardiovascular and muscular strain impair cognitive performance in amateur batters? A secondary question is: Are the results collected valid and can they be replicated in a test-retest setting?

Based on literature from the research rationale, it is expected that the demands associated with prolonged batting (shot replication and execution as well as repeated sprinting between the wickets) will cause fatigue of the muscular and cardiovascular subsystems. Further, the fatigue experienced will negatively impact on the allocation of cognitive resources, which will directly reduce a batter's ability to process information. Resultantly, cognitive impairment will follow prolonged intermittent activity.

1.6 Dissertation Outline

This dissertation will be constructed in the traditional block layout. The literature review will identify the novelty of the current investigation and provide sufficient detail for the reader to be adequately informed about the current research trends and findings. This chapter comprises a systematic-based review of the player requirements for successful batting, as well as a narrative review that covers the following topics: cognition, cognitive control and information processing; information processing models and how they apply to batting; theories of arousal, attention allocation and resource allocation; the impact of exercise on cognition; the mechanisms of cognitive fatigue and the fatigue mechanisms inherent to prolonged exercise. In the third chapter, the methods employed combined with a comprehensive review of the tools, protocols and procedures used to test the research hypothesis will be presented.

The subsequent chapter will highlight the main effects obtained from experimentation, where results from the various phases of experimentation will be presented sequentially: *phase 1*: schoolboy sample; *phase 2*: academy *test* session and *phase 3*: academy *retest* session. Results from the schoolboy sample are written in isolation, while the *test* and *retest* sessions of academy batters are combined. Following this, a brief comparison of schoolboy vs. academy responses will be presented. Each results chapter will cover the following topics; physical responses (sprint times, vertical jump and batting accuracy), physiological responses (heart rate and heart rate variability), ratings of perceived exertion and cognitive performance responses (psychomotor function, vigilance, attention, working memory, visual learning and memory, and executive functioning). In the penultimate chapter, the findings will be discussed with reference to the relevant literature presented from chapter 2. In the final chapter the reader will be presented with a brief summary of the procedures and main outcomes from the investigation, after which the statistical hypotheses will be addressed and the conclusions drawn.

CHAPTER II - REVIEW OF LITERATURE

Intermittent sports like cricket received little research consideration before 2005. The handful of studies that were conducted looked to establish how physiological, biomechanical and performance responses were affected by this activity profile (Stretch, Buys, Toit, & Viljoen, 1998; Stretch et al., 2000; Stretch, Nurick, Balden, & McKellar, 2004). Research also investigated the effects of equipment design with a large focus on increasing safety within cricket (Loock, Du Toit, Ventner, & Stretch, 2006). The stop-start nature of the game and accompanying periods of high- and low-intensity make assessment difficult. Arguably, the greatest challenge is in accurately replicating match play and specifically, the transfer of competition influences into laboratory-based settings. For these reasons, research is limited. In the last decade however, cricket research has shown steady growth, with countries such as Australia, South Africa and New Zealand directing research.

What has become apparent is that all facets of the game (batting, bowling, fielding and wicket-keeping) require substantial physical and physiological conditioning (Taliep, Prim, & Gray, 2010; Houghton, Dawson, & Rubenson, 2013). The increasing game demands and frequency of matches necessitates improved cricket-specific conditioning; and research is the only means to provide truly tailored education. While physical attributes are an important aspect of successful batting, the major differences between elite batters and their recreational counterparts are skill level and an improved ‘mental game’ (Balaji & Jesudass, 2011; Joste, 2012). In spite of this, no research has investigated cognition during batting, nor have the effects of prolonged batting on cognitive performance been explored. This paucity warrants research into how information processing is affected by prolonged intermittent batting periods. Furthermore, the cognitive nature of batting in itself and how batters tire from prolonged mental focus, requires understanding. Only when this understanding is facilitated can we accurately inform coaches as to the implications of fatigue and provide suggestions for performance improvement.

This review aims to establish (i) how batters process information and (ii) the importance of efficient cognitive functioning during batting. In the subsequent sections, a systematic-based review will detail the demands of cricket match play, the physical attributes required of batters and the inherent abilities necessary in successful batting. This will be followed by a narrative review of the cognitive requirements of batting and the associated mechanisms underlying successful batting. It also includes sections on how humans process environmental information and how stress (fatigue) affects this ability. The review concludes with a section on fatigue and the mechanisms of fatigue in prolonged exercise. It also seeks to understand how neuromuscular fatigue may impact cognitive processing and what the consequences of such impaired processing are on batting performance.

2.1 The Rise of Cricket Research

Cricket research forms a small area of research within the intermittent branch of sports science. While early research in this area received little attention, there are currently a large number of scientists investigating cricket. Undoubtedly, the pioneer of cricket research was Dr Richard Stretch, a South African researcher based in Port Elizabeth. His passion for cricket developed as a boy and once his professional cricket-playing career ended, he continued his passion for cricket from a research perspective. His initial research interests investigated the biomechanics of batting, equipment design and physiology of batting and bowling. In his latter career his focus shifted onto injury patterns, statistics and player profiling.

Dr Marc Portus was the forerunner of Australian cricket research and played a pivotal role in early cricket research. Like Stretch, his early research began in the biomechanics of sport, in which he obtained his Doctor of Philosophy at the University of Western Australia. Most of Portus' research was conducted in his time at the Australian Institute of Sport, where he established a seasoned research group with his colleagues and other researchers from Australasia. With assistance from Roger Bartlett, Bruce Abernethy, Damian Farrow, David Mann, Robert Duffield, Jacqueline Alderson and a number of their students, these researchers formed a hub for cricket research.

The scientist who has driven South African cricket research to the heights it now reaches is Professor Candice Christie. Christie is currently the leading cricket expert within South Africa and has established a formidable research group in South Africa, including researchers from other South African universities and Cricket South Africa. While her focus has been predominantly on batting, she has collaborated with Dr Janine Gray and Dr Benita Oliver where their focus is bowling biomechanics.

Although the above-mentioned specialists have investigated a variety of cricket and non-cricket-related topics, these individuals are considered the main contributing authors to the current body of knowledge apropos batting.

2.2 The Art of Batting

The evolution of cricket research demonstrates that there has been a shift in research techniques from qualitative, prediction-based models toward research that is now quantitatively evidence-based. This shift has produced results that are valid and reliable, facilitating a better understanding of the demands of batting, bowling and fielding alike. The increasing popularity of the game is another reason cricket has received continued attention.

Cricket is an interceptive open-skill team sport, where stressful situations requiring increased cognitive functioning frequently occur (Thelwell, Weston, & Greenlees, 2007). The interceptive nature of batting requires batters to have a specific set of abilities to intercept the ball successfully. Briefly, these include: hand-eye coordination, balance, agility and cognitive control (selective attention, decision making and motor coordination). Although cognitive control must be maintained throughout high- and low-intensity periods, it is probable that high-intensity periods require greater selective attention to maintain decision-making and batting performance. The ability to apply heightened attention and focus in these periods allows professional batters to excel above their amateur counterparts (Foskett, Ali, & Gant, 2009). It is suggested that batters outclass their opponents by employing coping strategies to micromanage performance, fatigue and stress (Slogrove, Potgieter, & Foxcroft, 2002; Thelwell, Weston & Greenlees, 2007). Strategies include; the use of self-talk, relaxation techniques, pre-match routines and goal-directed behaviours. Cognitive coping strategies are the most frequently employed approaches to coping with sources of stress and batters who are better able to cope with these stresses are more likely to succeed (Holt, 2003).

When batting for prolonged periods, batters are subjected to a number of elements that act on the body. It is likely that the most physically demanding aspect of batting is sprinting between the wickets (two demarcated popping creases 17.68 m apart). In so doing, batters must accelerate and decelerate their body mass to execute the run. When running frequencies are high eccentric fatigue of the lower limb musculature will result and recovery time will be long (Nicol et al., 1991; Noakes & Durandt, 2000; Christie, 2008). This type of fatigue alters skeletal muscle function and results in a reduction in muscle power and reduced strength and is often represented by slower sprint times and reduced force production (Christie & Pote, 2014; Christie et al., 2016; Goble & Christie, 2016). The resultant performance implications are an increase in potential run outs and a greater chance of injury (Mansingh Harper, Headley, King-Mowatt & Mansingh, 2006; Orchard, James & Portus, 2006). Consequently, batters must possess substantial strength to counteract fatigue of this nature (Nunes & Coetzee, 2007).

The recent popularity of cricket has led to a higher frequency of matches for professionals per season. Subsequently the demands placed on batters have increased while the opportunities for rest and recovery have decreased (Noakes & Durandt, 2000). Between 1970 and 1999 the number of playing days increased by 280% (35 days in 1970 vs. 99 days in 1999) and with the advent of Twenty20 cricket (in 2005), the seasonal demands have increased even further (Noakes & Durandt, 2000; Orchard et al., 2010; Petersen et al., 2009; 2010). With reductions in rest and recovery, it is likely that the consistency of performance will deteriorate while an increase in acute and chronic injuries will also be observed (Orchard, James, Alcott, Carter & Farhart, 2002; Orchard et al., 2010). The increased physical demand, which necessitates peak physical conditioning, has been a major force that has promoted cricket research in the last decade (Pote & Christie, 2016). Despite increasing research support, the literature currently available, specifically related to batting, is limited. In light of this, a systematic approach in the review of available literature was conducted.

2.3 A Systematic Overview of the Requirements for Successful Batting

The subsequent review (Section 2.3) is based on books and peer-reviewed journals obtained from five online resource databases between January and February 2014. A strategic search of Google Scholar, PubMed, Scopus, SpringerLink and Taylor & Francis, with the combinations of key phrases listed in Figure 1, disclosed 2445 journals. The initial review scrutinised papers according to title and abstract, where 55 cricket-related studies were extracted. Papers were excluded on the following basis; not related to the sport of cricket; not relating to batting; not relating to the physical demands required in batting; bowling, fielding and throwing related studies; conference abstracts, theses and editorials.

To ensure that the remaining 55 conformed to the selection criteria, each was then read and screened for a second time. Twenty-two peer-reviewed journals met the inclusion criteria and were selected for review. The reference lists of the included papers were hand searched for additional sources of information. Therefore, the subsequent review is based on 50 batting-specific studies conducted between 1955 and 2016. The majority of the included papers are current, with 43 of these published after the year 2000. Within the following section values are expressed as mean ± standard deviation (SD) and where appropriate effect sizes as '*d*'.

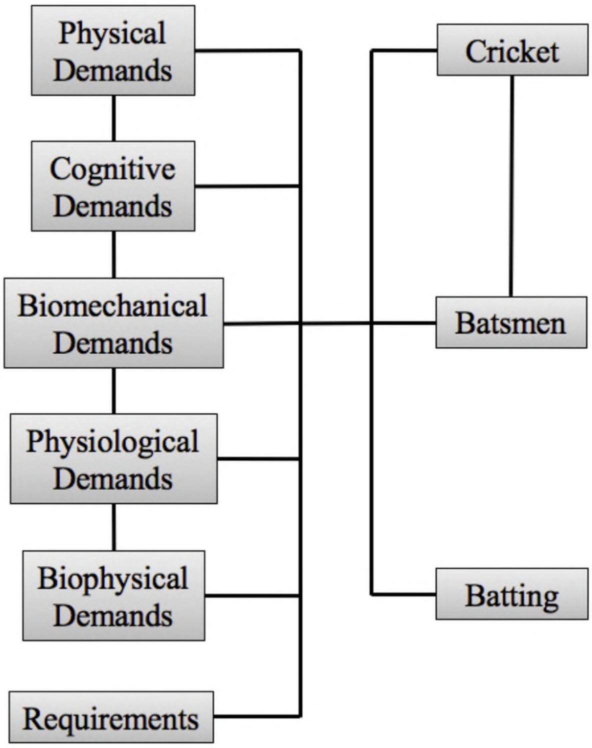


Figure 1: Search words and phrase combinations utilised in literature search.

2.3.1 Introduction

Batting is performed in a rapidly changing information-rich environment which involves the cricket ball, other cricketers, the field of play and even the spectators in the stands (Kruger, Campher, & Smit, 2009). It is characterised as an interceptive task that is intermittent in nature and is often performed under severe temporal constraints (Land & McLeod, 2000; Stretch, Bartlett, & Davids, 2000; Müller & Abernethy, 2006; Croft, Button, & Dicks, 2010; Mann, Abernethy, & Farrow, 2010; Sarpeshkar & Mann, 2011). Batting success necessitates a fine balance between inherent abilities and learned skills. Among these, batting success requires; a superior visual system, efficient neuromuscular control, heightened cognitive centres, physical fitness, strength, mental aptitude, and the ability to concentrate for prolonged periods. For batters with equal skill and ability, physical fitness is said to be a key determinant for success (Noakes & Durandt, 2000). This is especially true in the modern day game, where increasing seasonal demand places severe stress on the bodies and minds of batters.

2.3.2 The Importance of Skill, Perception and Motor Control

The interceptive nature of batting and the dynamic environment within which it is performed, necessitates critical focus and selective attention (Glazier, Davids, & Bartlett, 2002; Neave et al., 2004). Successful dynamic interception requires batters to achieve three goals (Stretch et al., 2000);

(i) ensure contact is made with the moving ball,
(ii) ensure contact has the intended velocity,
(iii) execute contact with the intended spatial orientation.

While this may seem simple, the temporal constraints placed on batters complicate this task (Stretch et al., 2000; Kruger, Campher & Smit, 2009; Müller, Abernethy, Reece, Rose, Eid et al., 2009; Croft et al., 2010; Mann, Abernethy, & Farrow 2010; Sarpeshkar & Mann, 2011). When facing a delivery between 90 - 150 km.h^{-1}, batters have between 425 and 700 ms from ball release to respond. With reference to a length delivery, once the ball has pitched 180-200 ms remain before the ball must be intercepted (Land & McLeod, 2000). In this time, batters must pick up visual information so that it can be encoded and perceived; select the required shot to be played; and then program the motor system to execute the desired shot. While Land and McLeod do not report on variable length deliveries, it is probable that the post-bounce time frame (180-200 ms) will be reduced for deliveries of a fuller in length. Likewise, a delivery that is very short would decrease the pre-bounce time frame while extending the post-bounce time period. Therefore, these variations in length are often deliberately employed as an effective way to maximise temporal and spatial uncertainty (Müller et al., 2006). Furthermore, bowlers also increase this uncertainty by creating late deviations in ball-flight (swing) or deviations off the surface of the pitch (seam bowling and spin) (Müller et al., 2006). To reduce these constraints and to execute a run-scoring shot, batters require a unique set of abilities. Briefly, these include; enhanced visual perception, neuromuscular control (hand-eye coordination) and an ability to interpret task-relevant information so that the visual and neuromuscular systems can act accordingly. What is less-clear, is the contribution that each of these play in successful batting.

2.3.2.1 Skill

Batting success is directly related to skill where skilled batters consistently outclass their less-skilled counterparts (Land & McLeod, 2000; Stretch et al., 2000; Campher, 2008; Croft et al., 2010; Sarpeshkar & Mann, 2011). What becomes apparent from the literature is that skill is not an innate ability, but rather a trait that is learned through hours of deliberate practise and playing experience (Wolpert, Ghahramani, & Flanagan, 2001). However, for batters with equal skill success is defined by other abilities (visual perception, information processing efficiency, motor control, strength and physical fitness). Batting-related skills are learned and honed when batters are exposed to an assortment of bowlers, in a variety of contexts, during ever-changing settings (environments/ matches /practise scenarios) and when performed in high frequency or over prolonged periods. The forthcoming section, unless otherwise stated, is written from a perspective of batters with equal skill.

2.3.2.2 Visual Perception

The visual system and how batters process visual information is arguably the most important determinant of batting success. Stretch, Barnard & Nurick (2002) contend, that the most important factor for success in batting is the ability to watch the ball throughout its flight-path, to assess the line and length and then to accurately and consistently execute a shot based on this visual information (concepts supported by Kruger, Campher, & Smit (2009). The temporal demands placed on batters, mean that batters who can observe and process visual information more efficiently, are at a distinct advantage (Stretch, Nurick & McKellar, 1999; Land & McLeod, 2000; Stretch et al., 2000; Kruger et al., 2009; Croft et al., 2010). A key strategy used by batters to overcome batting-related temporal constraints, is effective identification and interpretation of pre-delivery cues (advance kinematic information) inherent in the movements of opponents (Müller et al., 2006; Mann, Abernethy & Farrow, 2010; Sarpeshkar & Mann, 2011). For example, observation of the fielding positions of opponents often dictates the strategy of the bowler. The term ‘bowling to your field’ implies that a bowler and captain set a field that is most likely; (i) to get a batter out, (ii) reduce run-scoring opportunities, and (iii) defend the bowler against a bad delivery. Therefore, if a batter is to observe 'the field' (collective term for fielders and gaps between fielders) they can often anticipate the forthcoming delivery. This is especially true when a fielder is moved midway through an over.

Second, to anticipate pre-delivery ball characteristics, batters learn to 'read' the advance kinematic movements afforded by bowlers as they assume their run-up and approach their delivery stride (point of ball release) (Sarpeshkar & Mann, 2011). The cues most often observed (and the information obtained), include;

(i) the speed of the run-up and 'angle of attack' (speed and line of delivery),
(ii) the ball position in the bowler's hand (type of delivery: spin, swing or seam),
(iii) the spatial orientation of the bowler's body, particularly the distal arm segments (length of the delivery),
(iv) the ball-release height (length and bounce characteristics).

Recent evidence suggests that batters rely mostly on the latter cues to anticipate ball-flight characteristics, but the procedure employed will be unique for each player (Müller et al., 2006). These processes, often referred to as visual search strategies, help batters direct visual attention towards task-relevant information (Kruger et al., 2009). In doing so, batters increase selective visual attention (i.e. they are focused) which promotes effective information processing. Furthermore, skilled batters possess a superior ability in selecting task-relevant information which often contributes to better performances (Müller & Abernethy, 2006; Müller et al., 2006, 2009; Mann et al., 2010).

To assess visual perception and its effects on movement control, several studies have investigated batting performance during numerous occlusion paradigms (i.e. pre-ball release; pre-bounce; and no occlusion) (Müller & Abernethy, 2006; Müller et al., 2006, 2009; Mann et al., 2010). These investigations have aimed to determine; the capacity of the visual system, the extent to which batters utilise pre-delivery cues, which cues are most pertinent in successful ball interception and how these cues are used to facilitate neuromuscular control. Furthermore, researchers have used the initiation and orientation of a batter's foot movements as a measure of performance (Müller & Abernethy, 2006; Müller et al., 2006, 2009; Mann et al., 2010). In so doing, researchers have been able to propose how movement is facilitated and how these motor control patterns influence bat-ball interception.

It was demonstrated that pre-delivery information pick-up is dependent on skill and the time at which information was occluded (Müller et al., 2006). Moreover, skilled batters (compared to less-skilled) are better able to detect pre-release kinematic information and are also more effective in implementing this information to improve performance (Müller et al., 2006; Weissensteiner, Abernethy, Farrow & Müller, 2008; Mann et al., 2010). Similarly, skilled batters are also better able to detect pre-bounce information. From a fast bowling perspective, pre-delivery and pre-bounce information allowed skilled batters to attain higher (p<0.05) accuracy rates in predicting delivery type (in-swing or away-swing) and delivery length (short or full) (Müller et al., 2009). However, from a spin bowling perspective skilled batters' accuracy was superior in determining delivery type only, and not length. Furthermore, when ball flight information was not occluded, the differences in accuracy between skilled and less-skilled batters were less evident and performance was comparable. It appears then that the point of occlusion and the speed of delivery (factors that increase the temporal constraints of batting) compound batting-related differences.

A limitation of Müller and colleague's (2006) study, was that batters' were required to respond verbally, as such their task is not fully representative of batting. Mann et al. (2010) suggest that this type of experimentation creates a dissociation between perception and action, thereby reducing the validity of the results and their applicability to *in situ* batting. Therefore, Mann et al. (2010) investigated the role of perception-action coupling and its relation to batting success. Comparing skilled and novice batters in a 3x4 occlusion-coupling paradigm, Mann and colleagues confirmed that skilled batters were superior (p<0.05) in using pre-delivery cues to predict ball characteristics and improve response accuracy. Furthermore, these authors found that response accuracy improved in both samples with increasing degrees of perception-action coupling and longer ball-flight information. From this study, it is evident that batting is a task that is dependent on perception-action coupling and that the visual and motor systems are inherently linked.

It is clear that visual search strategies allow batters to anticipate the line and length of a delivery before the ball has been released. In doing so, batters are able to preselect potential shots that can be executed, ultimately allowing batters to react and respond timeously. However, once the ball has been released, the temporal constraints cannot be changed and as such batters are fully reliant on the capacity of their visual system. To assess the visual search strategies of batters, studies have used oculomotor tracking to determine the eye and head positions during ball-flight. It is noteworthy that the majority of studies have utilised bowling machines to study eye-tracking in batting, as such, advance kinematic information was unavailable.

For the subsequent section the following definitions are required (Purves, Augustine, Fitzpatrick, Katz, LaMantia et al., 2004);

(i) Fovea: area of the retina specialized for high acuity.
(ii) Saccade: ballistic, conjugate eye movements that change the point of foveal fixation.
(iii) Pursuit movements: slow tracking movements of the eyes designed to keep a moving stimulus on the fovea.

Research has indicated that once the ball has been released, batters employ smooth pursuit-tracking to track the ball for the initial 50-80% of its flight (Land & McLeod, 2000; Croft et al., 2010). Hereafter, an anticipatory saccade is made below the ball to a predetermined and predicted bounce location. The eye then fixates on this point until the ball bounces. Once detected, the head and eyes pursuit track the ball by moving rapidly downwards until interception occurs. The duration of initial pursuit tracking and the size of the saccade are said to be dependent on the skill of the batter (Land & McLeod, 2000). Skilled batters are more proficient at pursuit tracking and as such can make the anticipatory saccade earlier than less-skilled batters. Croft et al. (2010) support this theory and add that pursuit tracking is individual specific where even experienced batters have varied tracking patterns. What is clear is that skilled batters (compared to their less-skilled counterparts) are better able to use early ball-flight information to produce the saccade, allowing them to adopt an optimal striking position sooner (Sarpeshkar & Mann, 2011). This coupled with a smooth movement of the head are thought to be key areas that facilitate higher bat-ball interception accuracy.

It is now obvious that the role of the visual system to facilitate visual perception is paramount in batting. Batters with more efficient visual systems are at a distinct advantage, as this facilitates effective information pick-up and encoding. This information, in combination with efficient information processing will enable a batter to respond timeously in an already time-constrained task.

2.3.2.3 Neuromuscular Control

A determinant of batting success is an efficient link between the perceptual and the neuromuscular systems (Sarpeshkar & Mann, 2011). This link facilitates the initiation of foot movements that will optimally position the body to the ball's flight, line and length (Müller & Abernethy, 2006). Consequently, if the pre-delivery information obtained by the visual system is not succeeded by efficient neuromuscular control, the body of the batter will not be optimally positioned to time the bat-swing, and as such the quality of interception will degrade. This is especially true when the temporal constraints are increased (Müller et al., 2009).

Sarpeshkar & Mann (2011) posit that two schools of thought are believed to guide motor programming in interceptive sports: predictive control and prospective control. Predictive control is defined as a pre-programmed movement that is triggered at an appropriate criterion timing (Katsumata & Russell, 2012). In this control the pre-delivery information and early ball-flight is used to select and initiate the most appropriate response (preprogramed responses). Batters then use this predetermined motor program, that is well learned and organised prior to the execution of the movement, to facilitate a response to the approaching ball (Sarpeshkar & Mann, 2011). The only criterion in this form of control is that the batter needs to initiate the pattern at precisely the right time. This will ensure that the bat meets the ball in the predicted position with the correct timing. Conversely, prospective control is defined as a mechanism that uses continuous information to update and regulate action (Katsumata & Russell, 2012). Prospective control is guided by the supposition that no two movements are the same, and as such they are guided by different motor programmes (Sarpeshkar & Mann, 2011). In this mechanism, batters would use 'real-time' alterations, provided by the perceptual and motor systems, to continuously update task-relevant information as the ball approaches.

As noted previously, occlusion studies demonstrate that the facilitation of movement and the success of ball interception are dependent on the ball characteristics (line, length and type of the delivery [spin, swing, fast]), the time of occlusion, the degree of perception-action coupling and skill level (Müller & Abernethy, 2006; Müller et al., 2006, 2009; Mann et al., 2010). In regard to neuromuscular control, Müller & Abernethy (2006) hypothesised that the information necessary to guide foot movement was not the same as that required for bat-ball contact and in 2009, Müller and colleagues confirmed this theory. The authors found that while foot movements were dependent on pre ball-release information and early ball-flight characteristics, successful bat-ball interception had a greater dependence on ball-flight information. Once again, skilled batters were superior in all bat-ball contacts at all points of occlusion, however, skill-related differences were less obvious when vision was not occluded (Müller et al., 2009). It is possible that the enhanced ability of skilled batters to use pre-delivery information allows early facilitation of foot movements and hence improved response accuracy. Evidently, then, observation time and response accuracy share a linear relationship. In addition the quality of bat-ball interception is dependent on skill, information transfer between the visual and motor systems and ball velocity (which directly influences observation time) (Regan, 1997; Müller et al., 2009; Mann et al., 2010). These findings demonstrate two important batting implications; (i) bat-ball interception is not predictive but rather prospective, where success is facilitated with increasing ball-flight information, and (ii) the ability to utilise ball-flight information is highly dependent on skill. Müller et al. (2009) and Mann et al. (2010) suggest that early ball flight information allows batters to program the muscular system for initial bat positioning, while late-flight information allowed batters to fine-tune bat movements to improve ($p<0.05$) interception accuracy.

From these studies, it appears that the ability to intercept a fast moving cricket ball requires continual feedback from ball-flight characteristics before and after the bounce. It seems that the initial programming of foot movements utilises more of a predictive control that is based on pre-delivery information and initial ball-flight characteristics. These early foot movements allow batters to place the feet and body in a good position so that ball-striking is facilitated. However, this predictive control seems insufficient to facilitate quality bat-ball contact. The latter therefore requires an enhanced prospective control that allows minor alterations in motor programming and muscle recruitment. Based on the nature of batting and given that a large majority of bowlers try to deceive batters with late deviations in ball flight and also deviations of the pitch, it would seem that prospective control is a better suited mechanism for batting. Consequently, Sarpeshkar & Mann (2011) contend that batting uses a hybrid of predictive and prospective control, whereby batters utilise prospective control up to the 200 ms before interception, whereafter, a predictive movement is made to meet the ball in a future time and place. Based on the anticipatory nature of visual tracking and the early initiation of foot movements it seems plausible that batting also uses predictive control to facilitate success. Therefore, the hybrid theory suggested by Sarpeshkar & Mann (2011) is the most applicable theory to guide neuromuscular control in batting.

2.3.2.4 Information Processing

This global term details the process of detection of a stimulus, its perception and the facilitation and execution of a response. To the author's knowledge there are no studies that have assessed the information processing requirements while batting, consequently discussion on this topic is difficult. What is clear from the preceding sections is that successful bat-ball interception requires effort from the following cognitive domains;

(i) visual attention (to observe the ball, its flight and to determine the interception point),
(ii) working memory (to decide what should be done with the ball i.e. play or leave),
(iii) accurate decision making (to select and execute a shot), and
(iv) efficient processing speed and muscular control (so that shots can be executed with the correct force and timing).

Research has however investigated batters decision making processes in response to video footage of seam bowling (Taliep, St Clair Gipson, Gray, van der Merwe, Vaughan et al., 2008; Taliep & John, 2014). While the ecological validity in these studies were reduced by the use of video footage, they do indicate that skilled (compared to less skilled) batters have a superior decision making ability and that this is perhaps facilitated by a higher autonomy while batting. This is ultimately facilitated by a more effective use of attention, where skilled batters are better able to focus attention to the most important batting stimuli (Taliep et al., 2008). This finding supports the works of Wickens & Hollands (2000) who state that for the facilitation of visual perception, attention must be directed to only the most pertinent environmental information and be devoid of distractions. When this is done, processing speed can be improved and the information that is necessary for decision making and muscular control can be better relayed. Improved communication then allows the batter to make decisions under less time pressure, indirectly affording the batter additional time to fine-tune motor programmes and improve bat-ball interception (Sarpeshkar & Mann, 2011). Based on the above, batting success requires superior visual perception, effective processing of task-relevant information and advanced neuromuscular control. Importantly, each of these in isolation is meaningless, as batters also require intricate coordination (executive control) of these subsystems. The task of batting appears to have a high cognitive demand which requires continual interpretation of afferent task information. This information provides the basis of all efferent control which allows a batter to execute shots and score runs.

That being said, the intermittent nature of batting also requires batters to be physically strong to withstand the forces associated with intercepting the ball and also the forces acting on the body when jogging, running and sprinting. The subsequent section will highlight the physical requirements inherent in successful batting.

2.3.3 Movement Demands

In short, movement demands refer to the distances covered, the speeds batters achieve and also the total workloads batters encounter for a given period. This term also describes the way in which players cover these distances. These variables allow researchers, coaches and trainers to understand the demands placed on the bodies of batters when active. The gold standard of measurement today are global positioning satellite (GPS) devices; however, earlier studies relied on time-motion data to establish the movement demands of cricketers.

As far back as 1955, there has been interest in the quantification of player movement patterns (Fletcher, 1955). Fletcher focused on the activity profiles of cricketers and found that whilst batting, the majority of the time ‘at the crease’ was spent “facing the bowler”, “walking” and “running”. In an early estimation into the distances associated in scoring a century, Noakes & Durandt (2000) hypothesized that a batter would cover approximately 3.2 km. The corresponding activity period was 8.2 min, where batters were suggested to perform 180 (17.68 m) shuttles at an average speed of 24 km.h^{-1}. Duffield & Drinkwater (2008) conducted the first comprehensive time-motion study, comparing movement patterns between one-day and Test match centuries. Their results showed that in one-day cricket, batters reached the 50 and 100 milestones faster and spent less time being stationary and walking, than in test cricket. In one-day cricket, batters required 135.5 ± 21.4 min and 102 ± 18 balls to reach a century, compared to 213.4 ± 31.9 min and 160 ± 23 balls in Test cricket. During this period at the crease, batters spent 59.8 vs. 63.4% (one-day vs. test cricket) of their time stationary, 34.2 vs. 31.7% walking, 3.7 vs. 2.6% jogging, 1.7 vs. 1.0% striding and

0.6 vs. 0.4% sprinting. This equated to work-to-rest ratios of 1:47 and 1:67, demonstrating the higher intensities, strike rates and run rates inherent in one-day cricket.

The first GPS based study investigated the movement patterns of academy cricketers during Twenty20 (T20) match play (Petersen et al., 2009). Batters covered the least total distance (2.43 ± 0.45 km in 30 mins) compared to all other playing positions (Table I). In a follow-up study, Petersen et al., (2010) compared movement demands between playing positions and game formats (T20, one-day and Test cricket). The relative distances were similar to his previous findings and once again batters covered the least total distance between positions (T20: 2429 ± 657 m.h^{-1}; 50-over: 2467 ± 720 m.h^{-1} and Test cricket: 2064 ± 607 m.h^{-1}). From time motion analyses of 20, 50 and 90-over cricket for a six-year period (2003-2009), Houghton et al. (2011b) developed a 30-over batting innings (BATEX) to simulate the scoring of a one-day century (100 runs). This protocol showed batters to cover a total distance of 2171 ± 157 m.h^{-1} with a recovery ratio of (1:31)- data comparable to Petersen and colleagues (2476 ± 631 m.h^{-1}) (Houghton et al., 2011b). Later, the reliability of the simulation was confirmed and has since been employed in several batting studies (Houghton et al., 2011a; Houghton & Dawson, 2012; Pote & Christie, 2015, 2016).

Table I: The movement demands of batting in Twenty20, One-day and Test cricket compared to modern-day batting simulations. All values (mean ± SD).

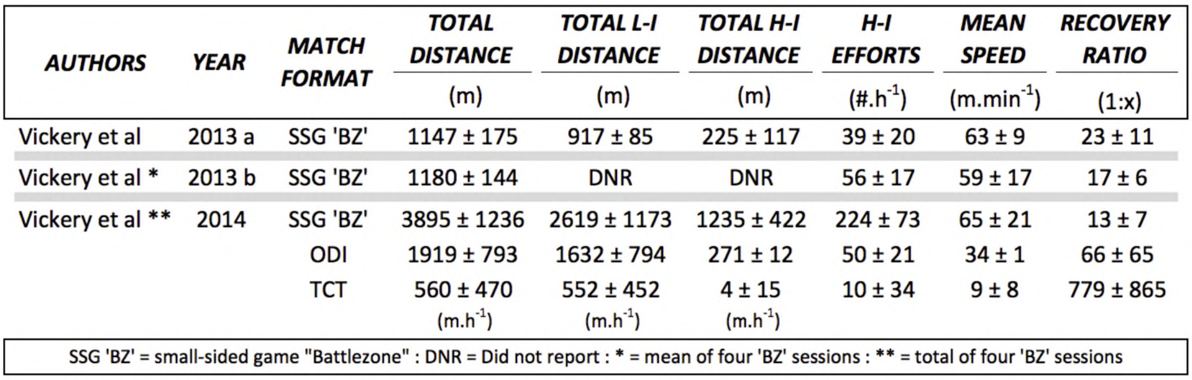
AUTHORS	***YEAR***	***MATCH FORMAT***	***TOTAL DISTANCE*** (m.h^{-1})	***TOTAL L-I DISTANCE*** (m.h^{-1})	***TOTAL H-I DISTANCE*** (m.h^{-1})	***H-I EFFORTS*** (#.h^{-1})	***MEAN SPEED*** (m.min^{-1})	***RECOVERY RATIO*** (1:x)
Petersen et al	2009	T20	4866 ± 900	4078 ± 1242	788 ± 416	76 ± 34	81 ± 8	DNR
Petersen et al	2010	T20	2429 ± 657	1970 ± 455	458 ± 202	15 ± 9	40 ± 11	38 ± 13
		ODI	2476 ± 720	2087 ±519	389 ± 201	13 ± 9	41 ± 12	50 ± 21
		TEST	2064 ± 607	1804 ± 528	260 ± 79	8 ± 3	34 ± 10	61 ± 10
Houghton et al	2011 b	ODI SIM	2171 ± 157	1910 ± 99	261 ± 58	DNR	36 ± 3	31 ± 3
Houghton et al	2012	ODI SIM	2216 ± 177	DNR	DNR	DNR	37 ± 3	32 ± 6

T20 = 20-over : ODI = one-day : TEST = Multiday game : ODI SIM = one-day simulation : DNR = Did not report

While the movement demands appear low, batters are also required to field during the match and when fielding before batting, the additional strain can negatively impact batting performance. Petersen and colleagues (2009) demonstrated that when fielding or wicket-keeping for 80 min, players would cover 8.14 ± 1.3 km and 6.43 ± 0.7 km, respectively. Therefore, when combined with batting workloads (2.43 ± 0.45 km), players would cover

10.57 km and 8.86 km, respectively. In the event that a batter batted for the whole innings, total distance per match would amount to, 15.43 km and 13.72 km for a fielder and wicket-keeper, respectively. In the unlikely event that a player batted for the full 50 overs (3 hr 30 min), they would cover ~8.7 ± 0.6 km during their innings with 0.5 km covered at sprinting intensity (Petersen et al., 2010). Furthermore, when batting a whole innings in T20 and test cricket, batters would cover a total of 3.5 ± 0.2 km and 13.0 ± 2.0 km, for the 20 and 90 overs, respectively. With regard to the activity profile, batters covered the second highest number of sprint bouts per hour (second to bowlers) in each respective game format, completing 15 ± 9, 13 ± 6 and 8 ± 3 sprints in T20, one-day and multiday cricket respectively (Petersen et al., 2010). Accordingly, the recovery ratio demonstrates that 20-over cricket comprises the highest intensity (1:38), followed by 50-over (1:50) and multiday cricket (1:61).

Table II: Movement demands required of batters during Battlezone. A comparison to one-day and traditional cricket training (TCT). All values (mean ± SD).



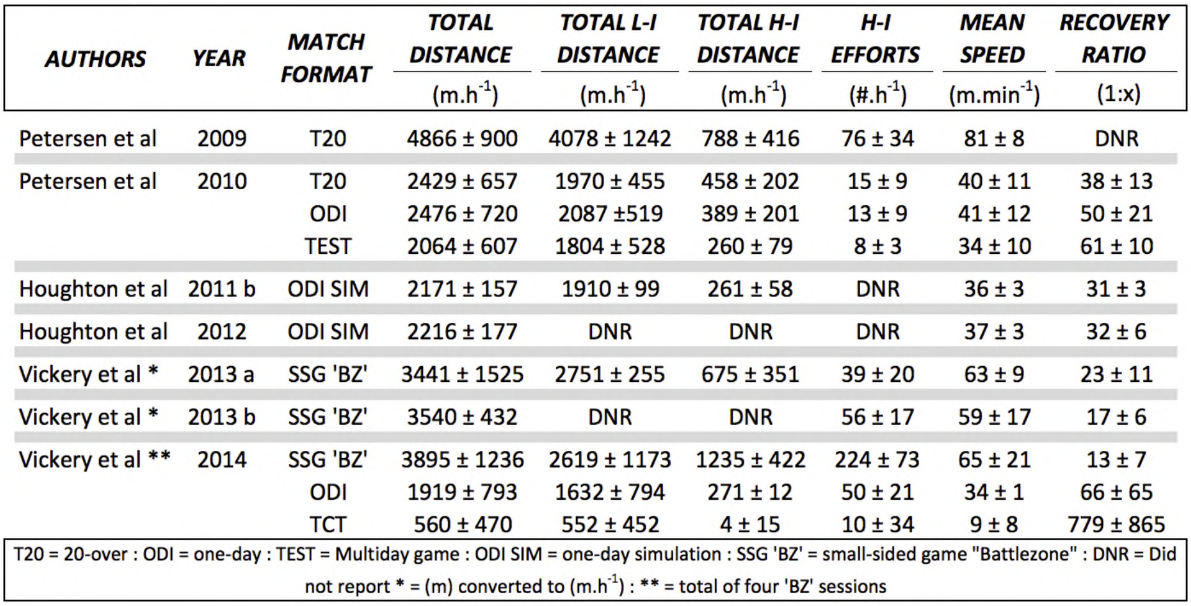
AUTHORS	***YEAR***	***MATCH FORMAT***	***TOTAL DISTANCE*** (m)	***TOTAL L-I DISTANCE*** (m)	***TOTAL H-I DISTANCE*** (m)	***H-I EFFORTS*** ($\#.h^{-1}$)	***MEAN SPEED*** ($m.min^{-1}$)	***RECOVERY RATIO*** (1:x)
Vickery et al	2013 a	SSG 'BZ'	1147 ± 175	917 ± 85	225 ± 117	39 ± 20	63 ± 9	23 ± 11
Vickery et al *	2013 b	SSG 'BZ'	1180 ± 144	DNR	DNR	56 ± 17	59 ± 17	17 ± 6
Vickery et al **	2014	SSG 'BZ'	3895 ± 1236	2619 ± 1173	1235 ± 422	224 ± 73	65 ± 21	13 ± 7
		ODI	1919 ± 793	1632 ± 794	271 ± 12	50 ± 21	34 ± 1	66 ± 65
		TCT	560 ± 470 ($m.h^{-1}$)	552 ± 452 ($m.h^{-1}$)	4 ± 15 ($m.h^{-1}$)	10 ± 34	9 ± 8	779 ± 865

SSG 'BZ' = small-sided game "Battlezone" : DNR = Did not report : * = mean of four 'BZ' sessions : ** = total of four 'BZ' sessions

More recently, movement studies have investigated the physical demands of small-sided game-based simulations ("Battlezone") comparing results to other cricket formats and training practises (Vickery et al., 2013a, 2013b; Vickery, Dascombe, & Duffield, 2014). In the first of these studies, the authors compared training loads in a repeated measures design between players during two Battlezone sessions (Vickery et al., 2013a). Contrasting Petersen's data, batters covered the greatest total distance (1147 ± 175 m), high-intensity distance (225 ± 117 m) and the highest mean movement speed (63 ± 9 $m.min^{1}$) during each bout (Table II). Vickery et al. (2013b) measured the same variables but manipulated Battlezone with four training modalities (field size, player number, field size & player number and rule changes). As Table II indicates, the values attained by batters were comparable to the 2013a study, however, the distance covered by batters was less than that attained by bowlers and fielders. This was attributed to the manipulations enforced in the first three modality changes.

In 2014, Vickery and colleagues compared Battlezone responses to traditional net-based cricket training and one-day match data. Battlezone demanded the greatest work load (3895 ± 1236 m.h^{-1}), when compared to traditional net-based training (560 ± 470 m.h^{-1}) and match play (1919 ± 793 m.h^{-1}). In contrast, one-day matches recorded higher ($p<0.05$), total overall distance (1716 ± 1315 m) compared to Battlezone (851 ± 222 m) and traditional net-based training (139 ± 119 m). Mean running speed was also highest in Battlezone (65 ± 21 m.min^{-1}), followed by one-day competitions (34 ± 1 m.min^{-1}) and traditional net-based training (9 ± 8 m.min^{-1}). Relatedly, the recovery ratio was substantially lower during Battlezone training (1:13) compared to one-day matches (1:66) and net-based practise (1:779). Vickery et al., (2014) conclude that in most instances the relative physical demand imposed during Battlezone either matched that of, or exceeded, one-day and traditional net-based cricket training.

Table III: A comparison of the movement demands associated with batting between 2009 and 2014. All values (mean ± SD).



AUTHORS	***YEAR***	***MATCH FORMAT***	***TOTAL DISTANCE*** (m.h^{-1})	***TOTAL L-I DISTANCE*** (m.h^{-1})	***TOTAL H-I DISTANCE*** (m.h^{-1})	***H-I EFFORTS*** (#.h^{-1})	***MEAN SPEED*** (m.min^{-1})	***RECOVERY RATIO*** (1:x)
Petersen et al	2009	T20	4866 ± 900	4078 ± 1242	788 ± 416	76 ± 34	81 ± 8	DNR
Petersen et al	2010	T20	2429 ± 657	1970 ± 455	458 ± 202	15 ± 9	40 ± 11	38 ± 13
		ODI	2476 ± 720	2087 ±519	389 ± 201	13 ± 9	41 ± 12	50 ± 21
		TEST	2064 ± 607	1804 ± 528	260 ± 79	8 ± 3	34 ± 10	61 ± 10
Houghton et al	2011 b	ODI SIM	2171 ± 157	1910 ± 99	261 ± 58	DNR	36 ± 3	31 ± 3
Houghton et al	2012	ODI SIM	2216 ± 177	DNR	DNR	DNR	37 ± 3	32 ± 6
Vickery et al *	2013 a	SSG 'BZ'	3441 ± 1525	2751 ± 255	675 ± 351	39 ± 20	63 ± 9	23 ± 11
Vickery et al *	2013 b	SSG 'BZ'	3540 ± 432	DNR	DNR	56 ± 17	59 ± 17	17 ± 6
Vickery et al **	2014	SSG 'BZ'	3895 ± 1236	2619 ± 1173	1235 ± 422	224 ± 73	65 ± 21	13 ± 7
		ODI	1919 ± 793	1632 ± 794	271 ± 12	50 ± 21	34 ± 1	66 ± 65
		TCT	560 ± 470	552 ± 452	4 ± 15	10 ± 34	9 ± 8	779 ± 865

T20 = 20-over : ODI = one-day : TEST = Multiday game : ODI SIM = one-day simulation : SSG 'BZ' = small-sided game "Battlezone" : DNR = Did not report * = (m) converted to (m.h^{-1}) : ** = total of four 'BZ' sessions

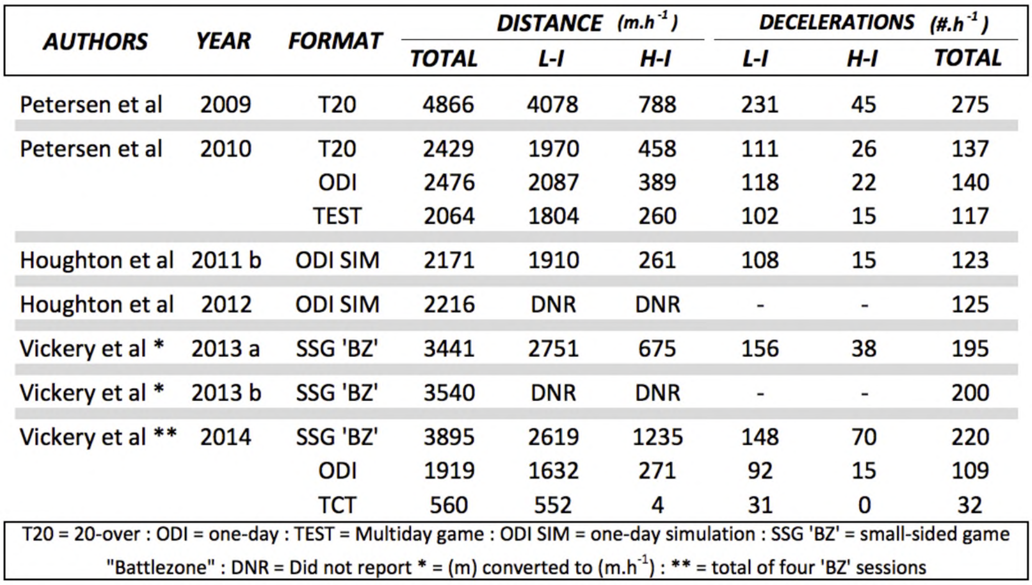
As illustrated in Table III, the distances (per hour) and relative speeds that batters cover across competition formats and in training simulations are considerable. What is apparent is that intensity of batting is dependent on match format and the constraints of practise. The highest competition intensity is observed during 20-over cricket, followed by 50-over and then multiday cricket. Therefore, the training profiles for these game formats must be designed accordingly so that they are competition-specific and prepare batters for the relative demand in each format. Importantly, the simulations and training tools developed by Houghton and Vickery provide a means to improve competition-specific strength and conditioning so that batters can better withstand the demands of competition.

2.3.4 Strength/Physical Demands

Successful ball interception and running performance require a substantial amount of strength to overcome the forces that act on the body (Noakes & Durandt, 2000). These forces are active while executing shots and when running between the wickets. Shuttle running, and hence running (between the wickets) requires both acceleration and deceleration actions (Lockie et al., 2012). Noakes & Durandt (2000) contended that the eccentric action of the leg muscles when decelerating is a major contributor to batting-related fatigue. Relatedly, repeated shuttle running has been shown to cause fatigue and impaired performance responses (L Houghton & Dawson, 2012; Lockie et al., 2012). It is estimated that batters, when scoring a century, undergo a minimum of 110 decelerations when changing direction between the wickets, contributing to the demand placed on the leg musculature (Noakes & Durandt, 2000). While this is an estimation, the following section looks to establish the number of decelerations required from previous movement pattern data.

While the calculations in Table IV are based on average distance covered, it provides detail into the hourly eccentric demand placed on batters. Therefore, greater total distance covered produces a higher number of decelerations and hence, higher eccentric load. Also, with a higher proportion of time spent in low-intensity activity, the proportion of decelerations changes accordingly. Nevertheless, each of these calculations are higher than that initially proposed by Noakes & Durandt (2000), suggesting that the eccentric load placed on the lower limbs is high. Therefore, to withstand the eccentric demands of running between the wickets, batters require concentric and eccentric strength of the leg musculature.

Table IV: Number of decelerations associated with distance covered by batters. Calculated as total distance divided by 17.68 m.



AUTHORS	**YEAR**	**FORMAT**	**DISTANCE** *($m.h^{-1}$)*			**DECELERATIONS** *($\#.h^{-1}$)*		
			TOTAL	**L-I**	**H-I**	**L-I**	**H-I**	**TOTAL**
Petersen et al	2009	T20	4866	4078	788	231	45	275
Petersen et al	2010	T20	2429	1970	458	111	26	137
		ODI	2476	2087	389	118	22	140
		TEST	2064	1804	260	102	15	117
Houghton et al	2011 b	ODI SIM	2171	1910	261	108	15	123
Houghton et al	2012	ODI SIM	2216	DNR	DNR	-	-	125
Vickery et al *	2013 a	SSG 'BZ'	3441	2751	675	156	38	195
Vickery et al *	2013 b	SSG 'BZ'	3540	DNR	DNR	-	-	200
Vickery et al **	2014	SSG 'BZ'	3895	2619	1235	148	70	220
		ODI	1919	1632	271	92	15	109
		TCT	560	552	4	31	0	32

T20 = 20-over : ODI = one-day : TEST = Multiday game : ODI SIM = one-day simulation : SSG 'BZ' = small-sided game "Battlezone" : DNR = Did not report * = (m) converted to ($m.h^{-1}$) : ** = total of four 'BZ' sessions

The importance of lower-limb and upper body strength in batting success is demonstrated in a study that isolated the contributions of isokinetic strength parameters to batting performance (Nunes & Coetzee, 2007). These authors contend that isokinetic strength values which emerged as the biggest contributors to successful performance in provincial academy batters were, knee flexor (hamstrings) and extensor (quadriceps) peak torque, average power and total work (Nunes & Coetzee, 2007). Flexor and extensor strength is necessary for batters to offset the demands imposed during repeated shuttle running and the prolonged semi-squatted position inherent in the batting stance. Furthermore, Nunes & Coetzee (2007) state that quadriceps strength and strength-endurance have a predictive power of 45% in batting success, whereas hamstring strength had a lower predictive power (12%). Resultantly, this strength profile is essential for batters.

This notion is supported in studies that have assessed maximal jump performance before and after batting (Houghton et al., 2011a; 2011b). The implementation of jump height as a test for muscular performance has been shown as a reliable measure of athletic performance (Markovic, Dizdar, Jukic &, Cardinale, 2004; McGuigan, Doyle, Newton, Edwards, Nimphius et al., 2006). The majority of studies assessing muscular performance have assessed both squat (SJ) and countermovement (CMJ) jump heights and the ratio between these measures to gain a holistic view of the concentric and eccentric contributions to power development. These tests are shown to provide a valuable and reliable method for assessing the stretch shortening cycle of athletes and their ability to generate explosive muscular power (Markovic et al., 2004; Lovell, Midgley, Barrett, Carter & Small, 2013). SJ height is a representation of the concentric contributions to jump performance, whereas the CMJ represents the stretch-shortening cycle and how this reflex contributes to jump height. The eccentric utilization ratio (EUR = CMJ/SJ) is used to represent the utilisation of the stretch shortening cycle and the performance-related changes in this cycle (McGuigan et al., 2006). A ratio above one is indicative of improved training status and an increased capacity to store potential energy. In contrast, a ratio below one suggests muscular fatigue and a reduced ability to utilize the stretch-shortening cycle.

Houghton and colleagues found that BATEX reduced SJ height ($p = 0.014$) in eight of nine participants (36.9 ± 4.1 vs. 35.0 ± 3.0 cm) while CMJ height was unchanged (36.9 ± 3.7 vs. 37.3 ± 4.2 cm: $p = 0.636$) (Houghton et al., 2011b). Relatedly, the decreased squat jump height, caused an increase in the eccentric utilisation ratio post-test (0.2 ± 4.7% vs. 6.6 ± 5.3%: $p = 0.051$, $d = 1.09$). Analysis of sprint times showed that sprint performance also deteriorated over time (Houghton et al., 2011a). The prolonged batting period resulted in slower ($p<0.05$) sprint times in stage 6, compared to stage 2 - a result supported by Pote (2013). The results from Houghton et al. (2011b) also suggests, contrary to Noakes & Durandt (2000), that the ability to store and use elastic energy, may be unaffected by prolonged batting simulations. This should however, be considered tentatively as the difference in eccentric utilisation was mostly due to changes in squat jump height with minimal change to countermovement height. In a subsequent study, both SJ and CMJ flight time were unaffected immediately after 30 overs of batting ($p = 0.078$; $d = 0.80$ and $p = 0.628$: $d = 0.08$, respectively) and 48 hr post-test (Houghton & Dawson, 2012). By contrast, 24 hours after batting SJ and CMJ flight time were substantially reduced ($p = 0.053$; $d = 0.80$ and $p = 0.009$; $d = 1.38$, respectively). Importantly, while fatigue is less evident immediately post-test, muscular fatigue is delayed to the following day where performance is substantially reduced. The implications of this are important for Test match cricket, where often cricketers bat on consecutive days.

The studies by Houghton and colleagues bear substantial implications for batting performance. Collectively, the decrements in muscular performance in response to prolonged batting periods require increased strength of the lower limbs to avoid muscular fatigue. Having been the only of the seven movement pattern studies to have assessed muscular performance, it is assumed that intermittent workloads of 2171 $m.h^{-1}$ and 2216 $m.h^{-1}$, respectively, are sufficient to induce decrements in sprint performance and potentially explosive power. Nicol and colleagues (1991) contend that when activity requires repeated stretch-shortening cycles in a prolonged setting (i.e. marathon running) fatigue is a likely result, where athletes will experience impairments in force production of both isometric and dynamic movements. Additionally, Noakes & Durandt (2000) propose that the eccentric demands of batting-related shuttle running is the most likely cause of muscular fatigue in batters.

While batters must possess lower body strength they also require upper body strength to play and execute shots with appropriate force and timing. In this regard, more successful batters are able to 'work' the ball more effectively around the field. Nunes & Coetzee (2007) contend that batting success is highly correlated to a batter's ability to generate high isokinetic internal shoulder rotator peak torque and average power at high movement speeds ($240^{o}.s^{-1}$). Conversely, batting success is not correlated with an ability to generate high peak torque of the internal shoulder rotators at lower speeds. The authors suggest that functional rotator strength is essential to attain high bat velocity for shot execution, while internal shoulder rotator endurance is needed so shots can be executed continuously without fatigue. This section illustrates, that whole body strength is essential to withstand the physical demands required in batting and to offset the time-course of fatigue. Batters who lack strength may be at a substantial disadvantage, may be more prone to injury or fatigue-induced changes in performance. While unknown, it is probable that improved conditioning and physical strength (i.e. improved training status) could delay fatigue and potentially reduce the cognitive strain associated with batting. This could be crucial in fatigue management and player performance; thus, further research in this regard is warranted.

2.3.5 The Physiological Demands of Batting

While still under-researched the physiological demands of batting have received the most research attention of all batting-related topics. This is by and large due to the ease with which these responses can be measured. The first batting-related study which measured physiological responses found that heart rate responses were similar in cool (22.6 ± 0.7 °C; heart rate of 121 ± 1 bt.min-1) compared to warm (32.9 ± 0.3 °C; heart rate of 122 ± 1 $bt.min^{-1}$) conditions (Gore, Bourdon, Woolford, & Pederson, 1993). In a match comparison, heart rate responses of batters were highest during 20-over cricket (149 ± 17 bt.min^{-1}) compared to one-day matches (144 ± 13 bt.min^{-1}) (Petersen et al., 2010). Further, despite batters covering the least distance between playing positions, they attained the highest heart rates of all playing positions. During a small-sided simulation, Battlezone, heart rates of 164 ± 12 bt.min^{-1} were measured compared to 159 (±12) bt.min^{-1} in one-day matches (73 %HR$_{max}$) and 153 (± 15) bt.min^{-1} during traditional net-based (56 %HR$_{max}$) cricket training (Vickery et al., 2014). Furthermore, similar response are also reported in studies that quantified the physiological profile of cricketers (Johnstone & Ford, 2010; Petersen et al., 2011)

Short duration high-intensity batting has been shown to elicit the highest physiological demand (145 ± 10.8 - 166 bt.min^{-1}) with batters exercising at approximately 89% of age-predicted heart rate maximum (Christie et al., 2008; Christie & Pote, 2014; Vickery et al., 2014, 2013a, 2013b). Prolonged batting also places a great deal of strain on the cardiovascular system (123 ± 11 and 157 ± 14 bt.min^{-1}), however, the overall intensity is less (73 %HR$_{max}$) than that reported in shorter duration batting (Houghton et al., 2011a; 2011b; Pote & Christie, 2015).

The rate at which batters consume oxygen and the corresponding change in ventilatory responses are also dictated by batting intensity and duration. In a profiling study, Gore et al. (1993) demonstrated that batters consumed 57 ml.kg^{-1}.min^{-1} (4.33 ± 0.2 L.min^{-1}) during a maximal performance test. During batting activity, Fletcher (1955) found that the caloric expenditure when required to run two out of six deliveries in the nets was 479.9 kcal.h^{-1} (2009 kj.h^{-1}). He then extrapolated the data to competition, estimating batters to consume 365.6 kcal.h^{-1} (1530 kj.h^{-1}). Short duration innings' (seven overs) have been shown to elicit an oxygen demand between 26.7 and 26.9 ml.kg^{-1}.min^{-1} (2538 kj.h^{-1}) (Christie et al., 2008; Christie & Pote, 2014). By contrast, batters required 36.65 ± 6.47 ml.kg^{-1}.min^{-1} to complete the BATEX simulation (Pote & Christie, 2016). These data show that the cardiopulmonary responses of batters are high when batting and that cardiovascular efficiency is required to effectively run between the wickets.

The sweat rates appear to be similar across short and long duration batting, but are significantly increased when environmental conditions are unfavourable. Gore et al. (1993) found that mean sweat rates (batters and bowlers) were higher (*p*<0.05) on warm days (0.70 ± 0.03 kg.hr^{-}1) when compared to cool days (0.54 ± 0.03 kg.hr^{-1}). In response to seven overs of batting, a mean sweat loss of 1.05 $L.h^{-1}$ was recorded (King, Christie & Todd, 2002). Furthermore, sweat loss was higher ($p<0.05$) when batters wore full cricket kit (1.05 ± 0.2 $L.h^{-1}$) compared to not wearing any protective kit (0.90 ± 0.2 $L.h^{-1}$). Comparable, prolonged batting induced a sweat rate of 0.8 ± 0.2 $L.h^{-1}$ over a 2 hr 20 min (Houghton et al., 2011a).

What is clear from these studies is that the cardiovascular strain placed on batters and the subsequent physiological demand is dependent on;

(i) the number of shuttles completed (distance),
(ii) the intensity at which these are completed,
(iii) the duration of batting,
(iv) the environmental conditions, and
(v) the training status of the batter.

2.3.6 Conclusion

This section has outlined the constraints associated with batting and the necessary skills and abilities required for successful ball interception. It has gone further to demonstrate that batting is a physically demanding task that requires strength and cardiovascular fitness to withstand the demands of repeated and prolonged match play. It has touched briefly on the information processing capabilities required in successful interception, but clearly lacks domain-specific literature to back this standpoint. To create understanding on the topics that have not yet been covered, literature from sources not relating directly to batting is necessary. Therefore, the remainder of this literature review will take a traditional, narrative approach. The first step in understanding batting performance from a cognitive standpoint is to establish what cognition means, how we cognate and how we act based on these decisions.

2.4 Cognitive Control and the Human Brain

There are two main schools of thought in contemporary cognitive theory; information processing and the adaptation processes of assimilation and accommodation (Cognition, 2016). While the later are deeply rooted within Piaget's theory of cognitive development and are characterised by an individual's perceptions of reality and how these perceptions guide thought and reasoning (Sternberg & Sternberg, 2012): they may lack applicability to a semi-autonomous task like batting. In contrast, information processing theory provides a framework for the basic processes present in all tasks humans complete on a daily basis. For this reason, information processing theory provides a better framework to study and understand batting-related processes.

The nervous system provides humans with the ability to perceive, adapt and interact with an ever-changing environment (Sternberg & Sternberg, 2012). It affords us the ability to retrieve, process and act on environmental information so that we can create and achieve goal-directed outcomes. These processes are collectively termed cognition (Matlin, 2008). Cognition or information processing is the ability to attend to external stimuli or internal motivations; to identify the significance of such stimuli; and to make meaningful responses based on these stimuli (Purves et al., 2004). It also encompasses how we acquire, store, retrieve and use knowledge (Matlin, 2008). Each action, irrespective of its constructs, requires a certain degree of cognitive activity and mental processing: however, the degree of cognition required is underpinned by task complexity (Wickens & Hollands, 2000). The mental processes encompassed by cognition include; perception, memory, imagery, language, concept formation, problem solving, reasoning and decision making (Matlin, 2008). Superficially, the cortical region responsible for cognition is the cerebral cortex (Sternberg & Sternberg, 2012). Between the presentation of a stimulus and generation of behaviour, it is the association cortices in the parietal, temporal and frontal lobes that are believed to control the diverse functions of the brain (Purves et al., 2004). Within the forebrain, the basal ganglia (a deeper structure within the forebrain) is responsible for the processing of information so that upper motor neurons can be primed (Purves et al., 2004). This structure consists of three deeper brain areas, including the; caudate, putamen and Globus pallidus (Purves et al., 2004). For cognition to take place, mental and attentional resources (the adenosine triphosphate [ATP] of information processing) are needed as these facilitate the processing of information (Kahneman, 1973; Wickens, 1984; Matthews & Desmond, 2007).

2.4.1 Basic Concepts: Cognitive Domains and Their Relevance to Batting

2.4.1.1 Attention

It is generally accepted that the brain cannot process all the information that it is inundated with (Marois & Ivanoff, 2005). To circumvent this issue, the brain will apply a discriminatory process by selecting the most pertinent information to process; this process is referred to as attention. A simple dictionary definition of attention is; ‘to take notice of something’ or ‘the action of dealing with something’. In information processing, attention is a term that describes an individual’s ability to ‘focus on’ or ‘attend to’ specific stimuli that are most relevant to task success (Kahneman, 1973; Wickens & Hollands, 2000). From a sports perspective, Baechle & Earle (2008) suggest that the ability to process both internal and external environmental information is termed attention. Attention can also be referred to as the effort invested in a task i.e. selective in nature (Kahneman, 1973). Selective attention is, therefore, effortful intentional focus on a task to ensure success in the task (Robert & Hockey, 1997). Attention can also be divided or sustained. Divided attention is the ability to perform more than one task at any given time. When attention is divided, success in a task is dependent on the nature of the task (its difficulty) and whether the two tasks require the same or different cognitive processes (Wickens, 2002). Sustained attention is defined as concentrating primarily on one particular task, while staying alert to changes in a secondary task (Matlin, 2008).

Attention is regulated in two manners, top-down or bottom-up processing (Sarter, Givens, & Bruno, 2001). Top-down processing is voluntary and is referred to as detailed, user-directed processing. Conversely, bottom-up processing is involuntary and involves attention captured by salient cues in the environment. Top-down and bottom-up processing are not mutually exclusive, but rather, represent overlapping organisational principals that work together to optimise performance (Sarter et al., 2001). What is evident is that attention is required in all information processing, irrespective of the task being performed. Further, in a task like batting, where time constraints are high and the margin for error low, effortful, top-down allocation of attention is pivotal. Importantly, once an athlete has become expert at a particular task the effort required, and hence resources, to perform the task are reduced (Hillman, Apparies, Janelle, & Hatfield, 2000; Hatfield, Haufler, Hung, & Spalding, 2004)

2.4.1.2 Resources

According to energetic constructs, resources refer to the ‘fuel’ or ‘energy’ necessary for cognitive processing (Matthews & Desmond, 2007). Resources differ according to the cognitive process required, and, are grouped together in a variety of pools (Wickens & Hollands, 2000; Young & Stanton, 2002a, 2002b). These resource pools are used differentially and resource allocation is dependent on the demands inherent in a task

(Matthews & Desmond, 2007). The concepts of attention, resources and resource allocation led to the formulation of a number of theories that attempt to explain human performance, fatigue and the regulation of human performance. These are addressed in a later section (2.4.3).

2.4.1.3 Perception

All information processing is initiated by stimulus detection and terminates with the object being perceived. It is this process, from initial detection to the realisation of a stimulus, which defines perception. Matlin (2008) describes perception as, the use of previous knowledge or experience to interpret stimuli that are registered by our senses. A further definition suggests that perception involves the mapping of one's own internal body representation of a stimuli (Papaioannou & Hackfort, 2014). Others contend that perception incorporates the establishment of meaning within the sensory signal, and, that this meaning is derived from the individual's past experiences (Wickens & Hollands, 2000). Evidently then, perception of stimuli requires an inherent link with memory. While perception is grounded in numerous theories, the basis for perception requires an understanding of sensory memory, pattern recognition and attention.

i) *Sensory Memory*

Once sensory systems detect environmental stimuli, the sensory store is the initial reservoir to hold this information (Papaioannou & Hackfort, 2014). Sensory memory, also referred to as sensory storage and the short-term sensory register, holds detected information in a relatively raw unprocessed form and for a relatively short period of time (Matlin, 2008). While information can be obtained from all the senses, the sensory system challenged depends on the nature of the task. The capacity of this system is said to be unlimited, however, the rate of decay is fast, with information held for approximately two seconds (Baddeley & Hitch, 1974). Once information has been detected, it travels via sensory neurons to the thalamus, where it is then directed to the appropriate region in the cortex (Purves et al., 2004; Sternberg & Sternberg, 2012). The internal structuring of the thalamus (neurons grouped by function) allows all types of information to be accommodated, sorted and transferred to the appropriate brain region (Sternberg & Sternberg, 2012).

ii) *Pattern Recognition*

This term refers to the process whereby the raw unprocessed data is transformed and organised (Matlin, 2008). In this process, the raw data is compared to information within other memory structures through bottom-up processing. Pattern recognition therefore facilitates perceptual processing.

Batters are reliant on visual information, and as such the visual system will detect and decipher the majority of the sensory information. These data travel from the retina, via the primary visual pathways (optic nerve) to the dorsal lateral geniculate nucleus of the thalamus and on to the primary visual cortex in the occipital lobe (Purves et al., 2004). The fundamental roles of a batters visual system would be to identify pre-delivery cues and ball flight characteristics. This will allow the visual system to determine and formulate patterns from the environmental information. On a subconscious and involuntary level, the ability to establish patterns early on in the delivery will be advantageous to batters. However, without the correct focus and attention, visual information may be lost and batters may increase the number of errors made while batting.

2.4.1.4 Vigilance/ Visual Attention

Rooted in the concept of attention, vigilance refers to the mental state in which attention must be maintained, so that particular stimuli from the environment can be detected over prolonged periods (Sternberg & Sternberg, 2012; McCallum, 2016). Previously, the term 'watch-keeping' has been used to describe vigilance (Kahneman, 1973). Visual attention is most important in tasks that require sustained attention for prolonged periods (e.g. air traffic controlling). The concept of vigilance is best described by the metaphor of a flashlight (Wickens & Hollands, 2000; Matlin, 2008). In this example the eyes act to focus only on environmental stimuli that are most pertinent to task success. Thiffault & Bergeron (2003) state that vigilance has both physiological and attentional properties; an increase in physiological arousal, attention allocation or effort, produces a like increase in vigilance. Many researchers have supported the hypothesis that a lack of attention or arousal incurs a vigilance decrement (Bowyer, Humphreys, & Revelle, 1983; Wickens & Kramer, 1985; Wickens, Mavor, & McGee, 1997; Sarter et al., 2001; Young & Stanton, 2002b Lenneman Sidrow, Johnson, Harrison, Vojta & Walker, 2013). Therefore, visual attention is facilitated by bottom-up processing, however, controlled through top-down processing (i.e.

environment stimuli attract the attention of the eyes, thereafter the individual would actively sustain attention).

Successful batting requires sustained visual attention for the entire duration of the innings. The intermittent nature of batting would, however, dictate a corresponding profile for visual attention (i.e. moments of sustained visual attention followed by minor breaks between balls and overs). This may reduce the load on the visual and attentional systems, allowing batters to perform for long durations.

2.4.1.5 Memory

Memory comprises encoding, storage and retrieval of learned information over time (Purves et al., 2004; Matlin, 2008) and is the result of perception, attention and learning (Underwood, 2016). The storage and retrieval of this information is dependent on the manner in which it was stored (i.e. rehearsal or chunking) and the effort invested in the storage process. The brain area fundamental in memory is the hippocampus in the temporal lobe and is responsible for both formation and retrieval of memory (Purves et al., 2004; Sternberg & Sternberg, 2012). This area is essential in learning, the formulation of associations between related items and in the spatial orientation of items in relation to one another and in relation to our body (Sternberg & Sternberg, 2012).

Two differing memory systems, have been qualitatively established in humans, declarative and non-declarative memory (Purves et al., 2004). Declarative memory refers to storage and retrieval of information that is available to consciousness and that can be expressed through language (i.e. your identification number). Conversely, non-declarative memory refers to retrieval of subconscious processes that have been learned overtime (i.e. skills learned – ball interception). Memory is also defined according to a temporal constraint (Purves et al., 2004). Literature surrounding the number and names of these classifications is contentious, however, generally speaking we refer to two temporal categories; short-term and long-term memory (Broadbent, 1957; Wickens & Kramer, 1985; Wickens et al., 1997; Wickens & Hollands, 2000; Hansen, Johnsen, & Thayer, 2003; Purves et al., 2004; Matlin, 2008). The acquisition and storage structures involved in declarative information include; the hippocampus, Wernicke's area (words) and the temporal cortex (objects and faces).

Conversely, the cerebellum, basal ganglia, and premotor cortex are the structures recruited in acquisition and storage of non-declarative information (Purves et al., 2004)

i) *Short-term Memory*

Memory researchers use the term short-term memory to refer to the primary or short-lived memory functions (Underwood, 2016). Short-term memory has also been described as working memory, active memory as well as immediate memory (Purves et al., 2004; Matlin, 2008). Baddeley (1992), states that working memory refers to the system that temporarily stores and manipulates information necessary for complex cognitive tasks. Similarly, Hansen et al. (2003) state that working memory is a complex system that holds only current information and that it is responsible for the storage and computation of information. The capacity of this memory structure is between 7±2 items and information can be held for approximately 18-20 seconds (Purves et al., 2004; Repovs & Baddeley, 2006; Matlin, 2008). Capacity is also dependent on the type of information stored and what the information means to the individual. For example, a batter may be able to remember more than 9 chunks of batting related information at one time, because the nature of the task is somewhat easy to him/her. Nonetheless, the limited capacity of working memory creates a bottleneck for other incoming information. Consequently, selective attention is pivotal in selecting only the most important information to be perceived and compared with working memory.

Arguably one of the most frequently cited models to explain working memory is that of Baddeley & Hitch (1974). This model describes working memory as containing three primary components: (i) the central executive, which controls attention and attention allocation; (ii) the visuospatial sketchpad, which holds visual and spatial information for use by the executive, and (iii) the phonological loop, which holds auditory information for use by the executive (Baddeley, 1992, 2010; Baddeley & Hitch, 1974; Hansen, Johnsen & Thayer, 2003; Repovs & Baddeley, 2006). In this model Baddeley & Hitch (1974) propose that the central executive receives, coordinates and integrates information from the other two components. These three components work together to encode information so that it can be stored in long-term memory.

ii) *Long-term Memory*

Long-term memory refers to the relatively permanent storage of information in the brain (Purves et al., 2004; Matlin, 2008; Underwood, 2016). Long-term memory can also include recent information, however, this information is in a fragile form as it has not yet been fully consolidated (Wickens & Hollands, 2000). It is the process of consolidation that actively stores information in long-term memory. The capacity of this memory structure is unlimited, where information can be stored for days, weeks and at times even a lifetime (Purves et al., 2004). The permanent changes made in the brain structure that create the existence of a memory (engram) depends on (i) the long-term efficacy of information transformation between the relevant synaptic connections and (ii) the growth and restructuring of the connections (Purves et al., 2004). Therefore, as we learn, our neural circuitry changes, becomes more efficient and the consolidation of memory is facilitated.

While long-term memory may not play a prominent role in a single innings, perceptions of current performance compared with past performances may have a substantial effect on the batters psychology and hence, performance. Through practice and the committal of shots to long-term memory, this memory structure will assist in decision making and working memory processes. Working memory, on the other hand, is crucial in batting. Each time a delivery is faced, batters will use working memory to select the appropriate shot for that delivery. Specifically, the role of the visual sketchpad is pertinent in the executive control of working memory (Baddeley & Hitch, 1974). The effectivity of the sketchpad to hold visual information so working memory can facilitate a decision will ultimately improve the entire cognitive process: indirectly allowing the batter more time to play the ball.

2.4.1.6 Psychomotor Function/ Speed of Processing

Psychomotor function, refers to the relationship between cognitive functions and physical movement (Noble, 2016). To fully understand this domain it is important to draw on areas of learning and skill. The development of organised patterns of muscular actions that are guided by environmental stimuli details psychomotor learning (Noble, 2016). Psychomotor skills, also referred to as perceptual-motor skills or sensorimotor skills, are those that involve the manipulation or movement of an object (through contraction of skeletal musculature) as well as the control of the body or parts of the body (Seidel, Perencevich, & Kett, 2005). The brain structures involved in motor coordination, control and motor output are; the cerebral cortex (precentral gyrus: houses the primary motor cortex), thalamus (sending of motor information), basal ganglia and cerebellum (motor coordination) (Sternberg & Sternberg, 2012).

The primary variables measured in the assessment of psychomotor function are the speed of the response and accuracy rates (Chmura Krysztofiak, Ziemba, Nazar & Kaciuba-Uscilko, 1998; Maruff Falleti, Collie, Darby & McStephen, 2005; Pietrzak Maruff, Mayes, Roman, Sosa & Snyder, 2008). In this domain, tests are designed to assess an individual's ability to perceive instructions and perform motor responses. Accuracy reflects the correctness or success with which the task was conducted. Reaction time, or perhaps more accurately referred to as response time, is defined as the time taken from the presentation of a stimulus to the initiation of the response (Pietrzak et al., 2008; Noble, 2016). From a neurophysiological perspective this time represents; encoding of sensory information; perception of the stimulus; thalamic conduction to the motor cortex; priming and firing of the upper motor neurons; conduction of the efferent signal to the muscles; synapse to the motor unit; and for the motor unit to effect the response.

The time constraints placed on batters when facing a bowler necessitate fast processing, while the interceptive nature of the task dictate a need for good muscular coordination. Psychomotor function is, therefore, an integral part of batting, where hand-eye-coordination and speed of processing are vital to success.

2.4.1.7 Executive Functions

This broad-spectrum term refers to the abilities that enable an individual to establish behavioural patterns and competencies, cognitive processes and ways of thinking (Etnier & Chang, 2009; Gurd, Kischka, & Marshall, 2010). Executive functions include control functions related to inhibition of responses, shifting of mental sets, monitoring and regulating performance, updating task demands, goal maintenance, planning, working memory, cognitive flexibility, introspection, problem solving, sequencing, sustained attention and multi-tasking, to name a few (Chan Shum, Toulopoulou & Chen, 2008; Knapp & Morton, 2013; McCabe McDaniel & Hambrick, 2010). These functions are performed under voluntary control and are said to occur in the frontal lobe of the pre-frontal cortex- specifically the dorsolateral areas of the prefrontal cortex (Hillman, Snook, & Jerome, 2003; Thayer et al., 2009; Mccabe et al., 2010; Teffer & Semendeferi, 2012; Lowe et al., 2014). Other researchers contend that the brain areas recruited in executive functioning are the anterior cingulate; lateral-ventral, and prefrontal cortex; and the basal ganglia (Sternberg & Sternberg, 2012). The Stroop colour-word interference task, go/no-go task, stop signal task, Eriksen flankers task, Wisconsin card sorting test, contingent continuous performance task and number various mental arithmetic problems are tasks most commonly used to assess executive functions (Hillman et al., 2003; Del Giorno, Hall, O'Leary, Bixby & Miller 2010; McCabe et al., 2010; Yanagisawa, Dan, Tsuzuki, Kato, Okamoto et al., 2010; Lowe et al., 2014).

In batting, executive functions encompass the collective processes whereby batters filter relevant from irrelevant environmental information; focus attention toward task-relevant information only; process and analyse this information; plan and select shots; and execute these shots. The collective domain is termed spatial problem solving, where a batter must detect and intercept the approaching ball with the goal of penetrating gaps in the field to score runs. These functions are fundamental to batting, where efficient and effective executive function will promote batting success.

2.4.2 Information processing

Information processing describes the procedures that humans use to extract stimuli to perceive their surrounding environment. The most widely accepted model to explain how we processes information is Wickens (1984) model of information processing (Figure 2). It shows how the cognitive brain identifies stimuli, facilitates perception and decision formulation and how responses are initiated and effected. The ability to adapt future responses through feedback makes human information processing unique. Lorist & Snel (1997), suggest human information processing to consist of several cognitive operations, mediating the transformation of a stimulus into a response. Consequently, every task that we face on a daily basis follows a distinct sequence of processes. According to Wickens (1984) these processes are; sensory processing; perception; cognition and memory; and response selection and execution. Tharp, Rundell, Lester & Williams (1974) propose that each stage of information processing is successive, additive and non-overlapping.

2.4.2.1 Human Information Processing: Wickens' Model Explained

The initial stage of processing is termed stimulus recognition. It begins by obtaining environmental information from the visual and auditory sensory receptors as well as from proprioceptive and kinaesthetic senses. The quality and quantity of the information that is registered has various limitations on each sensory system and as a result may influence the processes that follow stimulus recognition (Wickens, 2002). Once the information has been registered it reaches the level of the short-term sensory store. Even though the stimulus has been terminated the short-term sensory store prolongs the representation of the physical stimulus for a short period of time. Wickens, (1984a) contends that the short-term sensory store has three general characteristics: (i) it is pre-attentive, (ii) it is relatively veridical, and (iii) it is rapidly decaying. Kahneman (1973) Suggests that this stage of processing requires little to no recourses and that processing is relatively autonomous (bottom-up).

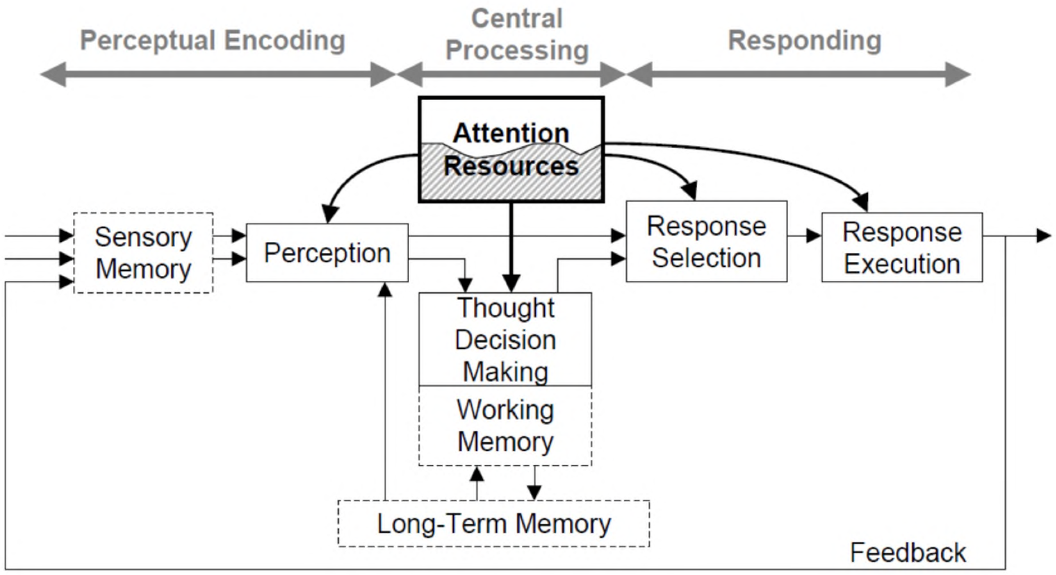


Figure 2: Wickens' model of human information processing (adapted from Wickens & Hollands, 2000).

Once preservation of the stimulus has occurred, increasingly high centres of the nervous system facilitate processing and as such, the need for resources increase. When information makes contact with these systems it is assigned with a unique neural code that has been learned and stored in the brain (this code is said to be based on previous encounters with similar stimuli). It is at this stage that Wickens describes the information as being perceived. Following perception, the information enters the central processing stage where information is categorised within a particular perceptual category and is guided by either bottom-up or by top-town processing. Bottom up processing may only require a judgement as to whether a stimulus is present or not, whereas, top-down processing requires detection of a stimulus, recognition, identification and categorisation of information (Wickens & Hollands, 2000). Therefore, perception is highly dependent on the complexity of the information presented. Tasks with greater complexity, require a greater number of sub-processes, and hence greater resources (Kahneman, 1973; Young & Stanton, 2002a).

Initially, central processing requires decision making so that the appropriate action can be performed. A decision may be made immediately, or the information can be stored while a decision is formulated (Wickens, 1984). This information can either be retained in working memory or stored permanently in long-term memory although this is, however, dependent on the mode of rehearsal. Therefore, the link between memory structures and higher cognitive centres is paramount for timeous decision making. Wickens posits that the junction between decision making and response execution is crucial to the outcome of performance.

Once a decision has been formulated and the response selected, an added series of steps must be carried out to initiate, with appropriate timing and force, the necessary muscular contractions to generate the desired action. This added phase is termed response execution. The decision to make the desired response is logically separate from its execution (Wickens & Hollands, 2000). Response selection does not specifically equate to response execution. Selection infers the choice of producing an action, while execution is the physical movement produced as a result of the selection (Wickens & Hollands, 2000). In this stage, the brain effects motor programmes that coordinate the musculature to produce the desired action. Importantly, the motor patterns are continually monitored and altered in the final stage of processing, to ensure the desired outcome is achieved.

Afferent feedback from the visual, auditory, proprioceptive or tactile modalities allows the brain to alter the necessary motor patterns to achieve goal-directed behaviour. Feedback can either be provided before the completion of the response (to augment the desired response) or after completion of the response (to provide information to future responses). This closed-loop nature provides information on the success or failure of the information processing cycle and as such, performance can be manipulated until the desired outcome is achieved.

2.4.2.2 A Case for Batting

Batting in cricket, and specifically prolonged batting, is a task that requires top-down processing as well as sustained and divided attention. It requires a batter to selectively attend to pre-delivery cues from opponents so the approaching ball can be detected and the appropriate shot selected and executed. If this is not performed timeously, it is likely that a batter will fail at their task (i.e. lose their wicket and hence fail to score runs). When Wickens' model is applied to batting, a typical information processing sequence would be as follows;

(i) Stimulus pre-processing at a sensory-perceptual level.

The auditory, visual, proprioceptive and kinaesthetic senses are used to identify all environmental stimuli (i.e. the crowd, the players on the field and their relative positions in space, the location of the ball and any motion being acted on the ball). This stage will utilise bottom-up and top-down processing to register the environmental stimuli. A skilled batter will use top-down processing to a greater degree, to isolate attention to only the most pertinent environmental information (the bowler and the ball).

(ii) Stimulus categorization.

At this stage, the batter will compare the current environmental stimuli to those from past experience. This will allow the batter to classify early ball characteristics to improve central information processing (i.e. watching the bowler approach the crease; observing advance kinematic information and any other subsequent actions on the ball; determining similarities of the present stimuli with those stored in memory from past experiences). At this juncture, the reliance on the visual system and visual perception is high and as such, top-down processing is the primary mechanism of attentional processing.

(iii) Response selection and organization

Using information from the stimulus categorisation and monitoring early ball flight information, a batter will predict the line and the length of the ball. From this information, working memory will be used to select the appropriate shot from their arsenal. While this stage still relies on the visual system, increasing responsibility is placed on the neuromuscular system in what is assumed to be predictive control.

(iv) Response execution

Based on all information obtained from the pre-delivery stride, pre-ball release and ball-flight characteristics this stage requires a batter to coordinate the muscular system to execute the selected shot. Almost fully dependent on the neuromuscular system and prospective control, the motor system executes motor patterns to intercept the ball at the predicted location. There is, however, still reliance on the visual system to provide information for the fine-tuning of motor programmes. When done efficiently, this will ensure precise interception.

(v) Feedback

First, continuous updating of ball-flight characteristics via the visual system allows the batter to manipulate the body and hence, the bat, so a shot can be executed with the correct timing, force and spatial orientation. Second, feedback of the ball once it has been hit is also interpreted. In this regard, an entirely new sequence of information processing must be performed. The batter must once again: (i) detect the ball off the face of the bat, (ii) perceive if the ball has entered a gap in the field, (iii) facilitate a “run” or “don’t run” decision and, (iv) initiate the appropriate motor response to beginning running. Furthermore, additional sequences will be performed while running to determine if a second or third run is possible, or to determine if the ball has crossed the boundary, in which case, running must be terminated.

This example illustrates that at each stage of processing there are a number of criteria that need to be achieved before the following stage is initiated. Also, it is evident that facing one ball does not require one sequence of processing, but rather, continual processing and updating of information. To achieve these criteria, resources must be available (Kahneman, 1973; Robert & Hockey, 1997; Wickens & Hollands, 2000). The need for resources increases because the latter stages are subject to interference, and as such, the mental effort to stay focused is high. Furthermore, as the example illustrates, successful interception of a single ball requires multiple cognitive processes. When scoring a century, these processes are continually repeated, requiring substantial resources, attention, concentration, and effort. In addition, batters continually need to monitor run rates, dismiss badgering from opponents and control their own psyche. Each of these components requires their own mental effort. The subsequent section will detail how these resources are allocated and how the task demands dictate the need for resources.

2.4.3 Theories of Information Processing: Resource Allocation

The subsequent models describe the capacities of neural, energetic and metabolic resources and how tasks tax these resources. Attentional resource theories are deep seated in cognitive psychology, and were developed under the following assumptions: (i) resources are fundamental in maintaining performance, (ii) resources are scarce and, (iii) that attention is necessary to mobilise resources (Robert & Hockey, 1997). The final assumption is based from the cognitive energetics basis and is fundamental to effort-regulation theories.

2.4.3.1 Resource Theory

Early research by Moray (1967), describes attention as having a limited capacity, much like the limited processing capacity of a general-purpose computer. Kahneman (1973) expanded this theory, stating that although attention was limited, it was not a structural limitation, but rather, it was flexible and shareable. He proposed that each individual had a single undifferentiated pool of resources that are available to all tasks and mental activities with considerable freedom. He thought attentional capacity was positively associated with physiological arousal, and that the ability to perform two separate but concurrent activities was dependent on the effective allocation of attention to each (Kahneman, 1973).

The capacity model was based on the premise of the inverted-U shaped function of efficiency (Yerkes & Dodson, 1908). In this model, a change in the arousal state of the organism would provide a corresponding change in performance. In states of under- or over-arousal, performance is poor, while optimal arousal levels produce the most effective performance. Kahneman (1973) suggested that when task demands increase, physiological mechanisms would produce an increase in the supply of resources; however, when demands were too high and supply insufficient, performance would deteriorate (Kahneman, 1973). The capacity theory is also applicable in a dual-task paradigm (where two tasks compete for the same resources), however, the overall demands on the information processing system are higher in this event (Wickens & Hollands, 2000). This could be on a purely cognitive level, where responders must be fast and also vigilant; or, in an exercise-cognition framework, where performance must be maintained in both regards. Kahneman's model states that a lack of resources would result in the deterioration of performance in either or both tasks (Van Duinen, Lorist, & Zijdewind, 2005). Contending theories at this time were that performance may become impaired due to a lack of input by the participants or by unavailability of other processing resources (Norman & Bobrow, 1975): a model later termed effort regulation.

This model of attention had many short comings and led to the formulation of other theories that explain the concept of attention, its allocation and utilisation. Wickens' Multiple Resource Theory proposes several pools of resources to exist, each with the ability to be used at varying stages of information processing (Wickens, 2002). He contended that resources are allocated and controlled in a four dimensional model, that contains three dichotomous dimensions: (i) two 'stage-defined' resources, used for perception and cognition or responding, (ii) two 'modality-defined' resources, used for auditory or visual perception and, (iii) two 'code-defined' resources for spatial or verbal processing (Wickens, 2008). The fourth dimension is nested within the visual modality and distinguishes focal from ambient vision (Wickens, 2008). This model suggests that each of these dimensions and their subdivisions require and use different resources. Furthermore, in a dual-task setting, where tasks require heterogeneous resources on any of the three dimensions, three phenomena are predicted to occur: (i) time-sharing will be more efficient; (ii) changes in the difficulty of one task will less likely influence performance on the secondary task and (iii) the performance operating characteristic will demonstrate a higher level of efficiency (Wickens, 2008). Therefore, dual task performance in this model is similar to that of the capacity model however, performance deteriorates only when tasks compete for resources from the same subdivisions of each dimension.

The major limitation of these models is that performance is said to be regulated involuntarily and that no volition exists. Audiffren, (2009) states that an involuntary mode of control contains two basal mechanisms: (i) arousal, a phasic short-lived and reflex response to input and (ii) activation, a tonic long-lasting and involuntary readiness to respond. 'Effort' was proposed as a third mechanism to coordinate arousal and activation, adding a voluntary aspect of attentional control (McMorris, Tomporowski, & Audiffren, 2009).

2.4.3.2 Effort Regulation Theory

Based on behavioural control research, effort regulation (self-regulation) proposes that to maintain or improve task performance, the individual must allocate sufficient effort within the task. As with resource theory, the concept of resources is fundamental to effort regulation, however, the important difference is in the interpretation of performance (Robert & Hockey, 1997). Resource Theory states that when resource demand exceeds capacity, performance degrades (Kahneman, 1973; Wickens, 2002, 2008; Young & Stanton, 2002b). In effort-regulation performance 'break-down' will result from failure in executive control of attentional resources, i.e. match effort to environmental task-demands (Matthews & Desmond, 2007; Robert & Hockey, 1997; Vohs & Heatherton, 2000). Therefore, if the individual is not sufficiently motivated to perform, performance will, in all likelihood, degrade.

Robert & Hockey (1997) proposed a compensatory control model of performance regulation, where: (i) performance is regulated through the effortful control of the individual and (ii) that performance is regulated by managing cognitive resources through the mobilisation of mental effort. Within this model, automatic and effortful control loops are responsible in the control of performance. All tasks begin in the autonomous loop, while more complex tasks (requiring more effort) invoke the effortful loop. It is the individual's perception of increasing task demands that mobilises effort, corresponding to a shift in control. Further, this shift is only temporary and when the perception changes, processing will resume in the autonomous loop. In both of these loops, performance regulation involves cost-benefit decisions with more complex processing requiring greater effort for effective processing.

An emerging theory to explain performance, from a regulation perspective, is the Malleable Attentional Resources Theory (Young & Stanton, 2002b). This model postulates that the limit on each specific resource pool is subject to change, and that this limit is directly related to task circumstances. Moreover, the size of resource pool varies positively with mental workload (i.e. increasing workloads will receive greater resources). This, however, is only true to a finite limit, in that excessive reductions in mental work load shrink attentional capacity and can result in performance degradation (Young & Stanton, 2002b). This theory states that the size of the pool is independent of variations in arousal or effort, and as such, attentional capacity and mental work load are directly related.

2.4.3.3 Cognitive Control

The Dual Mechanism of cognitive control, contends that cognitive control operates via two distinct operating modes: proactive control and reactive control (Braver, Gray, & Burgess, 2007). Proactive control is a mechanism where the individual actively maintains task-relevant information in a sustained manner, prior to cognitively demanding events, so that attention, perception and action systems can be optimally driven in a goal directed manner (Braver, 2012). Conversely, in reactive control attention is recruited after the occurrence of an important event, on a need-only-basis, rather than in advance to the event (Braver et al., 2007). Therefore, proactive control makes use of top-down processing and reactive control, bottom-up processing.

2.4.3.4 Performance Regulation in Batting

The physical nature of batting along with the effortful concentration and sustained attention required necessitates a dynamic model of performance regulation. Wickens' multiple resources theory is directly applicable to a complex, dynamic task such as batting, where the environmental information present can often be overwhelming. Multiple resources theory provides the best framework for batting-related information processing. Batting is a spatially orientated action that requires substantial visual input; where shot selection is heavily reliant on what the eyes see and shot execution on intricate motor control. Therefore, based on the constructs of this model (spatial vs. verbal; auditory vs. visual; perception and cognition vs. responding), resource allocation according to this model would be efficient and hence interference will be minimal.

That being said, the nature of running between the wickets requires a great deal of self-regulation and as such, effort regulation theory is as important for batting-related performance. Fatigue that will result from repeated physical exertion will no doubt affect cognitive performance, therefore, batters will require a great deal of effort to be invested to maintain cognitive performance. It is therefore proposed, that a hybrid model, incorporating multiple resource theory, effort regulation and proactive cognitive control is necessary. This is in line with the hybrid neuromuscular model proposed by (Sarpeshkar & Mann, 2011), where successful interception requires both predictive and proactive neuromuscular control. When these aspects are applied to batting, it is hypothesised that information processing will be maintained despite the physical and cognitively demanding nature of batting.

2.5 The Impact of Exercise on Cognitive Processing

Exercise and its beneficial lifestyle effects is currently a topical area, where the impact of exercise on mental health, well-being and cognitive performance has received substantial research attention (Tomporowski, 2003; Yanagisawa et al., 2010; Beaudoin, 2012; Chang et al., 2012). The primary research pathway has been the study of exercise in individuals who suffer from cognitive impairment (mild or chronic), with less focus on healthy samples. This review section will focus only on the effects of exercise in healthy, non-impaired samples, allowing better comparison to batters. Acute moderate-intensity bouts of exercise have been implemented most frequently in the study of exercise and cognition. The focus on prolonged and intermittent exercise has been minimal, and as such there is paucity in the literature. In a sporting context, few studies have quantified the effects of intermittent exercise on cognitive performance (Greig, Marchant, Lovell, Clough & McNaughton, 2007; Budde, Brunelli, Machado, Velasques, Ribeiro., et al., 2012; Casanova, Garganta, Silva, Alves, Oliveira & Williams, 2013) and less on batting (Neave et al., 2004).

2.5.1 Acute Bouts of Exercise

Some researchers have demonstrated that acute bouts of exercise have improved cognitive functioning (Audiffren, Tomporowski, & Zagrodnik, 2008; Yanagisawa et al., 2010; Ashnagar, Shadmehr, & Jalaei, 2014; Lowe et al., 2014), while others have reported either little or no change in performance (Hillman et al., 2003; Davranche, Burle, Audiffren & Hasbroucq, 2005; Luft, Takase, & Darby, 2009). What is apparent, is that in most cases the methodology used has directly impacted the results reported (Brisswalter, Callardeau, & René, 2002). Researchers contend that the magnitude of change is directly related to; when performance is assessed (during or after exercise); the nature and duration of exercise; and the type of cognitive task selected (Lambourne & Tomporowski, 2010; McMorris, Sproule, Turner, & Hale, 2011; Smith et al., 2010; Chang et al., 2012).

The tasks used to assess cognition have ranged from basic processes such as perceptual organization, information processing speed, and simple- and choice-response time, to tasks that measure memory and high-level executive control (Lambourne & Tomporowski, 2010). It is contended that acute exercise improves performance in tasks that are characterised by bottom-up processing, that are stimulus driven, automatic, implicit or unconscious (Audiffren, 2009). Conversely, tasks that are controlled through top-down processing, that are goal-driven, effortful, explicit or conscious often show decrements in response to exercise (Audiffren, 2009).

2.5.1.1 Psychomotor Function

In two separate studies, Davranche et al. (2005) and Davranche, Burle, Audiffren & Hasbroucq (2006) assessed visual choice-response times during a 15 minute moderate-intensity (2005: 50% mean aerobic power output; 2006: 50 $\%VO_{2peak}$) cycle ergometer protocol. A unique characteristic of each of these studies is that the authors used electromyography (EMG) to fractionate response time into, pre-motor and motor time. In so doing, the authors were able to determine the duration of mechanical transduction within the muscle fibres (motor time) and the duration of the early stages of information processing (pre-motor time). Audiffren et al. (2008) define premotor time as the interval between the onset of the response signal and the onset of EMG activity. Conversely, motor time is the interval between the onset of EMG activity and the initiation of the response (Audiffren et al., 2008). When compared to the control condition, 20 min of cycling improved ($p<0.05$) choice-response time while error rates were unchanged (Davranche et al., 2005). Furthermore, motor time was faster ($p<0.05$) in response to exercise, while pre-motor time demonstrated no effects ($p>0.05$). Despite differences in the sample and the exercise intensities implemented, these results are supported by Davranche et al. (2006) and Chang, Etnier, & Barella (2009). These authors did not, however, report on error rates. The improved motor time suggests that the early stages of information processing are not facilitated by exercise, but rather, it is the conduction of neural responses within the motor unit that were improved by acute exercise.

Kashihara & Nakahara (2005) studied choice-response time before and after 10 min of submaximal cycling at the lactate threshold (LT) and found that response times after exercise were faster ($p<0.05$), when compared to the control group. At a similar intensity (90% of the ventilatory turning point [VT]) 40 min of cycling improved choice response time ($p<0.05$) while response accuracy remained unchanged (Audiffren et al., 2008). These improvements were, however, only evident after 14 min of exercise and once exercise was terminated, response times were no longer different (Audiffren et al., 2008). Improved response times have also been reported during moderate-intensity exercise at 50% of maximal aerobic power (Davranche & Audiffren, 2004). Improvements in psychomotor function are also dependent on complexity, where 30 min of high-intensity exercise (70 $\%HR_{max}$) improved complex ($p<0.05$), but not simple, auditory choice-response time (Ashnagar et al., 2014). These authors failed to demonstrate differences in visual response times (simple and complex), therefore, the task modality also implicates performance changes. This complexity and modality paradigm is confirmed in the work of Luft and colleagues (2009).

It appears that the leading cause of performance impairment is exercise intensity. Moreover, cycling above the LT for 21 min has been linked to significant ($p<0.05$) decrements in psychomotor function (Ando Kokubu, Oda, Kimura, Hamada & Moritani, 2005). Similarly, after a supramaximal cycling bout (above 100% maximal power output) response times were also impaired, however, when intensity was ≥100% maximal power output no impairments were demonstrated (McMorris and colleagues, 2005). Cote & Salmela (1992) support this finding, showing that response times increased as a function of heart rate.

2.5.1.2 Vigilance

Accuracy of response is often used to determine the attention allocation of participants. It appears that, irrespective of the methodology utilised, vigilance is, for the most part, unaffected by acute bouts of exercise (McMorris et al., 2003; Davranche et al., 2005; Audiffren et al., 2008; Luft et al., 2009; Ashnagar et al., 2014). Kashihara & Nakahara (2005) found that response accuracy (percentage change) was improved ($p<0.05$) after exercise when compared to a non-exercising control group. Compared to pre-exercise responses, visual attention was improved ($p<0.01$) during submaximal cycling at an intensity of 60 $\%VO_{2max}$ (Pesce, Capranica, Tessitore & Figura, 2003). Further research is required to improve understanding on the effects of exercise on vigilance.

2.5.1.3 Memory and Executive Functions

The effects of acute exercise bouts on memory are poorly understood. This is partly due to difficulty in the differentiating between structures involved in memory and those of executive control; thus assessment of working memory in isolation is onerous (McCabe et al., 2010; McMorris et al., 2011). Further complicating differentiation is that the tasks that are used to measure executive functioning often indirectly measure memory performance (and vice versa) (McCabe et al., 2010). As such, the findings in the subsequent section include memory performance and executive functions.

Compared to a control condition, 40 min of submaximal exercise (60 $\%VO_{2max}$) improved speed of working memory ($p<0.01$) during a task-switching test, and response accuracy on a Brown-Peterson test (Tomporowski & Ganio, 2006). At a similar intensity and duration (40 min at 60 $\%VO_{2max}$) cycling improved ($p<0.05$) long-term memory (delayed recall) but had no effects on working or short-term memory (as measured by a set-switching task and Brown-Peterson test) (Coles & Tomporowski, 2008). The authors contend that exercise-induced arousal may have influenced the encoding and consolidation of information within long-term memory, thus improving delayed free-recall. Speed of working memory was facilitated ($p<0.05$) and accuracy unaffected ($p>0.05$) following a test to volitional exhaustion, indicating that high-intensity exercise also facilitates memory performance (Luft et al., 2009). A recent meta-analysis confirms that acute bouts of intermediate (50-75 $\%VO_{2max}$) activity facilitate working memory response time but impair accuracy of performance (McMorris et al., 2011). However intensities ≥ 80 $\%VO_{2max}$ are detrimental to memory functions.

As far back as 1977, exercise has been shown to improve executive functioning (McGlynn, Laughlin, & Bender, 1977). The majority of studies since then have provided evidence of improved executive functioning in response to moderate-intensity exercise (Sibley, Etnier, & Masurier, 2006; Yanagisawa et al., 2010; Lowe et al., 2014). Both Sibley et al. (2006) and Yanagisawa et al. (2010) demonstrated that Stroop colour-word performance improved in response to moderate-intensity exercise (20 minute self-paced treadmill protocol and 10 minute cycle ergometer at 50 $\%VO_{2peak}$, respectively). In both tasks, response times improved and error rates were unchanged indicating that response inhibition and selective attention were unchanged over time. Compared to a minimal exercise condition (35 min of cycling at 30-40 revolutions per minute), response inhibition (Stroop task) was better ($p<0.05$) following 35 min of incremental cycling (+10W.min^{-1}) at 30 %HR reserve (Lowe et al., 2014). In addition, a marginal improvement in response inhibition between minimal and vigorous exercise (+10W.min^{-1} at 50 %HR reserve) was also reported. At the same intensities Lowe and colleagues (2014) found that executive functioning was unchanged in the go/no-go and stop signal tasks; suggesting that the effects of exercise are dependent on the task administered.

Similarly, Kamijo, Nishihira, Hatta, Kaneda, Wasaka et al. (2004) found that response time in the go/no-go task was also unaffected after high-intensity cycling (test to volitional exhaustion). Additionally, Kamijo and colleagues (2004) observed that ~18 min of medium-intensity cycling at a constant workload (RPE of 12-14) facilitated response times in the same task. In a follow-up study, Kamijo, Nishihira, Higashiura, Hatta, Kaneda et al. (2006) found medium-intensity exercise also facilitated ($p<0.01$) response time in a go/no-go task, while no effects were observed after low- and high-intensity cycling. Further research by this group tested the same intensities against a Eriksen flankers task and confirmed that medium-intensity exercise facilitates executive function (Kamijo, Hayashi, Sakai, Yahiro, Tanaka & Nishihira, 2009). These results show an intensity-dependent effect of exercise on executive functions, a theory reported by Pesce et al. (2011).

Vigorous activity has yielded mixed effects on executive functioning (Hillman et al., 2003; Luft et al., 2009; Lowe et al., 2014). Hillman et al. (2003) found that 30 min of exercise at 83.5 $\%HR_{max}$ improved executive control in an Eriksen Flankers task. In contrast, Chang, Tsai, Hung, So, Chen, Etnier (2011) found that 30 min of moderate-vigorous intensity exercise improved problem solving and quality of planning, but not rule adherence and performance speed. Del Giorno et al. (2010) demonstrated that 20 min of cycling at 75% of the lactate threshold improved executive control while higher intensities (100% of LT) impaired executive control. This was demonstrated by fewer total errors, fewer preservative errors and fewer false alarms at lower intensities.

2.5.1.4 Summary

These data show that acute bouts of low-moderate-intensity improve most aspects of cognitive functioning following exercise. Performance during exercise has shown mixed results, with a tendency toward decreased cognitive functioning. This may however, be a result of dual-task interference (Wickens, 2008; Lambourne & Tomporowski, 2010). Higher-intensities seem to impair performance in a number of tasks, but have also improved functioning in a handful. Collectively, the results show that task sensitivity, duration and intensity of exercise and the time of assessment are important considerations when quantifying cognitive functioning.

2.5.2 Prolonged Exercise

Prolonged exercise studies have primarily measured response time, with little focus on vigilance, memory and executive function. What becomes apparent from the literature is that prolonged and acute bouts of exercise have similar effects on cognition. Performance improvement seems dependent on exercise nature and intensity, the nature of the task, and when performance is assessed.

Brisswalter Durand, Delignieres & Legros (1995) found that psychomotor function and vigilance were impaired during ~57min of incremental cycling at 50% peak power output. At a higher intensity (70% peak power output), prolonged cycling improved choice-response times ($p<0.05$) for the first 40 min of exercise, however, hereafter response time deteriorated ($p>0.05$) (Serwah & Marino, 2006). The maintenance of response accuracy in Serwah & Marino's study also suggest that vigilance was unaffected by prolonged exercise. Similar improvements in response times are reported after one hour of cycling at 60 $\%VO_{2max}$ (Tomporowski Cureton, Armstrong, Kane, Sparling & Millard-Stafford, 2005), 75% of maximal work capacity (Hogervorst, Jeukendrup & Jolles, 1996) and at 70% of VT (Chmura et al., 1998). In addition, Hogervorst et al. (1996) found that their cycling bout improved response inhibition in a Stroop task. Specifically, response time in the non-interference and interference trials were faster ($p<0.05$) post-exercise compared to pre-exercise. Collectively, these results show that prolonged cycling improves executive functioning.

Collardeau, Brisswalter, & Audiffren (2001) found that 90 min of constant intensity running had mixed effects on response times. After 10 min of running, response times were impaired (255 ± 23 ms; $p<0.05$) compared with pre-test (246 ± 20.6 ms); however, for the remainder of the protocol response times were faster. Also, at the 40th minute response times were 4.48% ($p<0.05$) faster than pre-test responses, supporting the result obtained by Serwah & Marino (2006). Collardeau et al. (2001) investigated how carbohydrate ingestion during a prolonged 100 minute run at VT impacted cognition. The authors reported no changes in response times in the control group, but significantly improved choice-response time ($p<0.05$) in the carbohydrate ingestion group. With no changes in simple response time, the authors contend that carbohydrate ingestion improves complex cognitive performance after exercise.

2.5.2.1 Summary

Most research has implemented low-moderate-intensity exercise, and results indicate that exercise of this nature facilitates psychomotor function, vigilance and executive functioning.

It appears that the facilitative effects of prolonged exercise are duration dependent, with 40-60 min being optimal. Longer durations and higher intensities appear to decrease cognitive functioning, however, further research is need to clarify the effects of prolonged high-intensity exercise.

2.5.3 Intermittent Exercise

In a randomised control trial, Lemmink & Visscher (2005) demonstrated that intermittent cycling neither improved choice-response times nor response accuracy ($p>0.05$). Compared to the control condition, effect sizes indicated small improvements in response times (*pre*: $d = 0.34$; *block 2*: $d = 0.44$; *block 3*: $d = 0.44$) and moderate improvements in response accuracy (*pre*: $d = 0.69$; *block 2*: $d = 0.74$; *block 3*: $d = 0.61$) in the exercising group. Budde et al. (2012) found that selective attention was unaffected following a maximal intermittent exercise protocol (achievement of HR_{max}). A post-exercise interaction effect of activity level and performance was, however, observed; where participants with higher training status' improved ($p<0.05$) selective attention post exercise.

Intermittent activity improved second-half response times ($p<0.05$) during a 90-minute soccer simulation (Greig et al., 2007). By contrast, error rates were lower ($p<0.05$) in the first half, compared to the second half of protocol, indicating that vigilance deteriorated over time (Greig et al., 2007). It is possible, however, that the increase in error rates could be due to a speed-accuracy trade-off, where players improved speed at the expense of accuracy. Also simulating soccer activity, Casanova et al. (2013) reported lower ($p<0.05$) response accuracy over time, in both amateur and professional players. However, accuracy was better in the highly skilled players throughout the protocol. Casanova et al. (2013) attribute this to the superior gaze patterns and behaviours of the skilled players (discussed in the subsequent section). This result was confirmed by Bullock & Giesbrecht (2014), who found that aerobic fitness levels and response time were highly correlated ($r = -0.63$; $p=0.02$). Once again, performance was better in individuals with higher aerobic fitness.

2.5.3.1 Perceptual-Cognitive Processing

While the systematic review section presented the perceptual cognitive processing in cricket related studies, research has also been conducted in other intermittent sports (Ripoll Kerlirzin, Stein & Reine, 1995; Roca, Ford, McRobert & Williams, 2011; Afonso, Garganta, McRobert, Williams & Mesquita, 2012; Casanova et al., 2013). To establish the relationship between perceptual-cognitive processing and intermittent exercise, most studies have utilised a combination of response accuracy, visual search patterns and verbal reports of cognitive processes. McRobert, Ward, Eccles & Williams (2011) found that skilled batters had superior response accuracy when predicting the position of the cricket ball in the strike zone. Similarly, improved response accuracy was reported by Roca et al. (2011) and Afonso et al. (2012), and to a degree by Casanova et al. (2013). Contrastingly, Ripoll et al. (1995) found that skilled boxers (compared to less-skilled) improved accuracy ($p<0.05$), but only in complex task situations. No difference was observed in simple tasks.

Soccer and volleyball studies also indicate that skilled players produce more effective search behaviours than less-skilled players (Afonso et al., 2012; Casanova et al., 2013; Roca et al., 2011). The improved strategy (as indicated by a greater number of saccades and reduced fixation duration) facilitates improved anticipatory performance, and hence response accuracy (Mann, Williams, Ward & Janelle, 2007; Mann et al., 2010; McRobert et al., 2011; Sarpeshkar & Mann, 2011). However, an upper limit to performance is yet to be determined. Ripoll et al. (1995) demonstrated that expert boxers (compared to novices) had improved search economy, utilising less frequent fixations with longer duration. Although the idea here is the same as that of Roca et al. (2011), McRobert et al. (2011), Afonso et al. (2012) and Casanova et al. (2013), the mechanism of improved efficiency is clearly different. This could be due to the varying nature of boxing compared to soccer, volleyball and cricket. Boxing is a one-on-one sport, conducted in close proximity to one's opponent. Therefore, the time that you have to respond to the opponent's attack is greatly reduced in comparison to other intermittent sports. This evidently promotes alternative search behaviours, compared to other intermittent sports.

Casanova et al. (2013) found that professional soccer players, when compared to amateurs, exhibited improved search efficiency at the start of each half. However, as protocol duration increased, a trend of decreasing search efficiency was observed. In this regard, all players made fewer fixations of longer duration to a lower number of locations (Casanova et al., 2013). This 'breakdown' in visual performance, was supported by reduced response accuracy ($p<0.05$) later in the protocol. Furthermore, the reduction in accuracy at an individual level could result in higher match-related mistakes that would directly influence the team's performance. Coupled with physiological fatigue, this could explain why there are more goals scored in soccer games towards the end of each half, and specifically towards the end of each game (Casanova et al., 2013).

2.5.3.2 Summary

The information presented above is, to the author's knowledge, all the data available in regard to intermittent exercise and its effects on cognitive performance. What is clear is that the impact of intermittent exercise on cognitive performance is variable. Much like the literature on acute and prolonged exercise, the difference in results can be attributed to discrepancies in methodologies. Evidently, skill and physical fitness also have significant implications for cognitive functioning in an intermittent context. Highly skilled players and those who have higher cardiovascular fitness experience less fatigue, and incur fewer decrements during intermittent activity. Duration and intensity of the intermittent protocol also seem to affect cognitive performance.

2.5.4 Conclusion and consequences for batting

Acute, prolonged and intermittent exercise have beneficial effects on cognitive functioning. However, a number of meta analyses and systematic reviews confirm that the magnitude of the benefit correlates with the following moderators (Tomporowski & Ellis, 1986; Tomporowski, 2003 Lambourne & Tomporowski, 2010; Smith et al., 2010; McMorris et al., 2011 Chang et al., 2012);

(i) the nature and duration of exercise,
(ii) the activity level and the skill level of the participant,
(iii) the type of cognitive tasks used to assess performance,
(iv) the time of day at which assessment takes place, and
(v) when performance is assessed (during, immediately after or following post-exercise rest).

In the most recent of these meta-analyses Chang and colleagues (2012) provide the following guidelines. Benefits are larger for fit individuals who perform physical activity for 20 min or longer at any intensity. Lower intensities provide more benefit when the tests are performed immediately after exercise, whereas, higher intensities have more durable effects that can be observed even following a delay. Importantly, none of the studies presented have assessed cognitive performance before, during or after physical activity that is also cognitively demanding.

From a batting perspective and seeing that intensity and duration of batting differ according to game format, it may be likely that cognitive functioning may be impaired by batting at high intensities and facilitated at moderate-low intensities. Additionally, it is probable that prolonged batting periods may impair cognitive function, whereas acute bouts of batting may improve cognitive functioning. Finally, it may be possible that these benefits may only be accrued following batting and perhaps not during batting. However, the type of competition played and the varying intensity and duration of match play are important and as a result, the application of previous findings are not clear cut. Most probably, cognitive performance will mirror the results observed in response to intermittent exercise, where cognitive function will be highly dependent on the duration and intensity of the batting bout. For example in a T20 format, where the intensity and the scoring rates of batting are high, it would be presumed that the associated physical and cognitive demands would result in impairment of batting-related cognitive performance. However, the duration of batting in this format will never exceed 20 overs for a single batter and will more likely comprise10 overs on average. Therefore, the short duration of batting may not allow sufficient time for a batter to experience cognitive decline and batting impairment. Comparatively, in Test cricket (90 overs per day for five days) prolonged batting durations are common, where batters are often at the crease for a full day, which could result in batting-related cognitive impairment. In contrast, the intensity and scoring rates are low in this format and as such batting-related demands can also be low. Therefore, to apply an intensity- or duration-related theory to this intermittent task would be misplaced. While this conclusion has no scientific literature to substantiate these claims it indicates the need for extensive research in batting-related cognitive impairment.

2.6 Assessing Cognitive Effort with Heart Rate Variability

Heart rate variability is a physiological parameter that assesses the beat-to-beat variations within heart rate. This measure allows researchers to determine the unique balance between the sympathetic and parasympathetic branches of the autonomic nervous system: functions essential in maintaining homeostasis within the body (Luft et al., 2009). Variations in heart rate are generally assessed through time domain and frequency spectrum analysis (Malik, Bigger, Camm & Kleiger, 1996).

2.6.1 Time-domain analyses

These measures are calculated at any specific point in time or from the intervals between successive, normal complexes. SDNN (ms) refers to the standard deviation between all beat-to-beat (N-N) intervals and reflects all cyclic components responsible for variability in the period of time being assessed (Malik et al., 1996). SDNN, therefore, is an estimate of total heart rate variability. RMSSD (ms) calculates the square root of the mean of the sum of squares differences between adjacent N-N intervals. RMSSD is the most commonly used parameter in heart rate variability analyses (Malik et al., 1996) and is often employed as it is mathematically robust (Corrales, de la Cruz Torres, Esquivel, Salazar & Orellana, 2012). Both SDNN and RMSSD are used as indicators of parasympathetic activation of the heart (Buchheit, 2014). PNN50 and PNN30 (%) are calculated as the percentage of adjacent N-N intervals that differ by more than 50 and 30 ms, respectively, and are frequently assessed to facilitate interpretation of heart rate variability (An, Kulkarni, Nagarathna & Nagendra, 2010).

2.6.2 Frequency-spectrum analyses

Frequency-spectrum components divide the heart rate signal into separate frequency ranges. The most widely used spectrums in the case of mental workload, are low-frequency (0.04-0.15 Hz) and high-frequency (0.15-0.4 Hz) (Jorna, 1992; Malik et al., 1996). The most common representations of the low- and high-frequency components are power and central frequency. The power variable reflects the total variance within the band (ms^2), while the centre frequency represents the frequency at which the power spectrum is split into two equal portions (Hz) (Billman, 2013). While contentious, low-frequency power is modulated by baroreflex activity and demonstrates both sympathetic and parasympathetic activity (Al-Ani, Munir, White, Townend & Coote, 1996; Elliot, Payen, Brisswalter, Cury & Thayer, 2011; McDuff, Gontarek & Picard, 2014). Other researchers believe that low-frequency power has a dominant sympathetic component (Pagani, Lombardi, Guzzetti, Rimoldi, Furlan et al., 1986; Malliani, Lombardi, & Pagani, 1994; Montano, Ruscone, Porta, Lombardi, Pagani & Malliani, 1994; Billman, 2013). The high-frequency component (often referred to as respiratory sinus arrhythmia) reflects vagal influence on the heart and is often used to reflect parasympathetic modulation (Jorna, 1992; Berntson, Bigger, Eckberg, Grossman, Kaufman, et al., 1997; Hjortskov et al., 2004). In addition, high-frequency power corresponds with changes in breathing frequency, with an increase in power during inspiration and a decrease during exhalation (Al-Ani et al., 1996). McDuff et al. (2014) states that the ratio between low- and high-frequency power (LF:HF) reflects sympathetic modulations, while others believe it is an indication of sympathovagal balance (Hjortskov et al., 2004; Taelma, Vandeput, Vlemincx, Spaepen & Van Huffel, 2011). The normalised components of the low- and high-frequency bands are mathematically derived from the LF:HF ratio (Burr, 2007), and are often used to represent a more easily understood representation of sympathovagal balance: sympathetic (LFn.u.) and parasympathetic (HFn.u.) (Pagani et al., 1986; Montano et al., 1994; Al-Ani et al., 1996; Malik et al., 1996; Taelman et al., 2011).

Most recently, Billman (2013) has suggested that the low- to high-frequency ratio does not accurately measure sympathovagal balance. Billman (2013) contends that previous researchers have defined the LF:HF relationship on naive assumptions of complex non-linear interactions between sympathetic and parasympathetic nervous systems. His theory has gained support (Reyes del Paso, Langewitz, Mulder, van Roon & Duschek, 2013), however, more research is needed to elucidate this.

2.6.3 Heart Rate Variability and Cognitive Workload

Research investigating cognitive workload through heart rate variability has mostly studied the effects of psychosocial stressors and their relation to cognitive performance. Few studies have combined physical activity, cognitive workload and heart rate variability; therefore, the implications of physical activity on heart rate variability parameters are unclear. Traditional (non-exercise related) research indicates that heart rate variability parameters are sensitive to changes in cognitive workload (Hjortskov et al., 2004; DiDomenico & Nussbaum, 2011) and that time domain parameters are correlated with cognitive performance (Luft et al., 2009). A number of researchers have used heart rate variability to examine the responses of the autonomic nervous system to mental and physical stressors; results have demonstrated the following (Jorna, 1992; Berntson et al., 1997; Malik et al., 1996; Hjortskov et al., 2004; Luft et al., 2009; Mukherjee et al., 2011; Taelman et al., 2011; Mukherjee, Yadav, Yung, Zajdel & Oken, 2011; Mateo, Blasco-Lafarga, Martinez-Navarro, Guzman &

Zabala, 2012; Billman, 2013; Luque-Casado, Zabala, Morales, Mateo-March & Sanabria, 2013; Cinaz, Arnrich, La Marca & Tröster, 2013);

(i) lower SDNN and RMSSD values are associated with tasks that require greater attentional demands,
(ii) a decrease in heart rate variability represents an increase in mental effort,
(iii) tasks that require higher degrees of executive control elicit decreases in the frequency components, specifically the high-frequency band,
(iv) an increase in mental effort decreases the low-frequency power component, and
(v) an increase in the LF:HF ratio is characteristic of sympathetic dominance.

In spite of this, the mechanisms explaining these changes are still poorly understood. Research indicates that time-on-task and heart rate variability share an inverse relationship (Jorna, 1992; Luque-Casado et al., 2013). Here, the initial stress imposed by the task increases heart rate variability, however, once the task is underway responses stabilise and heart rate variably decreases.

2.6.4 Heart Rate Variability and Physical Activity

The lack of literature on exercise-related changes in heart rate variability is due to the difficulty in distinguishing factors responsible for changes in parameters. Research shows that heart rate variability decreases in response to physical activity (Kamath, Fallen, & McKelvie, 1991; Al-Ani et al., 1996; Javorka et al., 2002; DiDomenico & Nussbaum, 2011; Peçanha, de Paula-Ribeiro, Nasario-Junior & de Lima, 2013). DiDomenico & Nussbaum (2011) report substantial decreases in SDNN during exercise, where the magnitude of decrease is mediated by the type of effort (isolated vs. whole body movements - $p<0.033$) and the movement frequency (high vs. low - $p<0.001$). Studies measuring heart rate variability before, during and after physical activity, report a decrease in heart rate parameters, both during and immediately after exercise (Kamath, Fallen & McKelvie, 1991); whereafter, heart rate variability gradually increases overtime (Javorka, Zila, Balhárek & Javorka, 2002). During post-exercise recovery, low- and high-frequency power increase, but do not return to pre-exercise levels (Peçanha et al., 2013). Time domain parameters are also sensitive to exercise, with physical activity decreasing ($p<0.05$) SDNN, RMSSD and PNN50 (Javorka et al., 2002).

Following five min of recovery, low- and high-frequency power were significantly higher ($p<0.05$) when compared to immediately after exercise (Peçanha et al., 2013)- a result reported only in highly trained athletes. These responses remained elevated ($p<0.05$) for five minutes (i.e. min 5-10), after which experimentation was terminated. Javorka and colleagues (2002) assessed time domain and frequency parameters for 35 min following physical activity and found that all indices increased ($p<0.05$) over time, but did not return to pre-exercise resting in this timeframe. Following exercise, low-frequency power was consistently higher ($p>0.05$) than high-frequency power, but not significantly so (Javorka et al., 2002; Peçanha et al., 2013). The mechanism of change following exercise is thought to be the resultant increase in blood pressure and breathing frequency (Jorna, 1992; Taelman et al., 2011). Conversely, the reduction in workload following the cessation of exercise causes a shift from predominantly sympathetic activity to increasing parasympathetic modulation (Javorka et al., 2002; Peçanha et al., 2013). As the rest period increases, autonomic modulation increases both sympathetic and parasympathetic activation. While the increase in sympathetic activation needs to be further elucidated, changes are believed to be linked to alterations in baroreflex activity from the resultant changes in blood pressure (Kamath et al., 1991; Al-Ani et al., 1996; Javorka et al., 2002; Peçanha et al., 2013).

Al-Ani et al. (1996) measured changes in spectral components before and after a 6 week training program. The authors found that isometric muscle contractions decreased high-frequency power ($p<0.05$), both before and after training (Al-Ani et al., 1996). The intervention decreased resting heart rate ($p<0.05$), increased maximal oxygen consumption ($p<0.05$) and increased average heart rate variability at rest ($p<0.05$). Peçanha and colleagues (2013) also observed a higher resting heart rate variability in trained athletes, compared to less-trained athletes. To the author's knowledge, no studies have measured heart rate variability in response to intermittent exercise.

2.7 Mechanisms Explaining Altered Cognitive Functioning

The following mechanisms have been proposed to contribute to exercise-induced changes in performance. No model is considered the 'gold standard', neither do any of these models stand in isolation. The foundation of these theoretical perspectives are the fields of cognitive psychology, cognitive neuroscience and psychophysiology (McMorris et al., 2011). The exact mechanisms pertaining to improved cognitive functioning are still poorly understood, and, further research is needed to elucidate this.

2.7.1 Arousal and Cognitive Energetics

Based primarily in cognitive psychology and psychophysiology this theory suggest that the stress imposed by exercise increases physiological arousal, augmenting performance (Yerkes & Dodson, 1908; Kahneman, 1973; Robert & Hockey, 1997). Central to this theory is the inverted U-shaped function of efficiency and the assumption that cognitive performance is dependent on the availability of resources (Lambourne & Tomporowski, 2010; McMorris et al., 2011; Chang et al., 2012). Firstly, arousal would improve attention and the allocation of resources to fulfil task demands, and as such, cognitive functioning would improve (Kahneman, 1973; Wickens & Hollands, 2000; Young & Stanton, 2002b; Wickens, 2008). Relatedly, the improvement in functioning is dependent on the level of arousal, with over- or under-arousal resulting in reduced performance (Yerkes & Dodson, 1908). Where resources are unavailable and arousal too high, deterioration in cognitive functioning would be imminent. Secondly, performance will be regulated by the quality of effort assigned to the task (Robert & Hockey, 1997; Young & Stanton, 2002b). If the effort invested in the task is insufficient, or the required workload too easy (creating a situation of mental underload), performance will also deteriorate. Conversely, with sufficient effort, cognitive functioning will be maintained or improve.

Based on this theory, exercise of moderate-intensity and acute duration will improve cognitive functioning. Conversely, strenuous, high-intensity activity of a prolonged nature or an exercise duration that is too short, will reduce cognitive performance. In addition, when exercise and cognitive performance are required in tandem (i.e. during exercise), a dual-task scenario arises and performance will be subject to resource availability and effort-regulation. This theory has been used to describe performance changes in a number of studies (Pesce et al., 2003; Tomporowski, 2003; Staal, 2004; Mann et al., 2007; Lambourne & Tomporowski, 2010; McMorris et al., 2011, 2009; Chang et al., 2012).

2.7.2 Reticular-Activating Hypofrontality Model

Previously known as The Transient Hypofrontality Theory, Dietrich's model, contends that the brain, in order to regulate both physical and cognitive performance, makes profound changes to the way in which metabolic resources are allocated (Dietrich & Audiffren, 2011). The rationale of this theory is based on three fundamental neuroscience principles: (i) the brain has a finite energy supply, (ii) bodily motion is an extremely demanding task for the brain - in computational terms, and (iii) information processing in the brain is based on competitive interactions among neurons (Dietrich, 2009). Therefore, when physical and cognitive performance is required, the brain will augment the allocation of neural resources. This is because activation cannot be maintained in all of its neural networks simultaneously (i.e. activity in one structure must come at the expense of others). The brain then moves metabolic recourses from less active neural structures and allocates these to the structures that are in critical need at the time. Dietrich (2009) contends that the brain does this in a hierarchical manner with a top-down approach. The hierarchical nature of removal means that brain areas that facilitate the highest cognitive functions will be affected first, whereas areas that support basic functions will be taxed last. Therefore, when exercising, the primary structures that would require resources are the motor cortex, the cerebellum and, of course, the exercising muscles. According to this theory, resources will be provided to these structures at the expense of structures within the prefrontal cortex and perhaps the limbic system (Dietrich, 2009).

While the acceptance of the mechanism within this model is contentious (Chang et al., 2012; Luft et al., 2009; McMorris et al., 2011), support is growing (Del Giorno et al., 2010; Dietrich & Audiffren, 2011; Boecker, Hillman, Scheef, & Struder, 2012).

2.7.3 Neuroendocrinology Theory

The application of this model is proposed for acute bouts of exercise only, and as such, the applicability to prolonged or intermittent exercise needs further clarification. Based from a psychophysiological perspective, the model supports an inverted-U principal of performance. It postulates that intermediate exercise will facilitate optimal physiological arousal, whereas, low- and high-intensity exercise result in poor arousal (McMorris, 2009). From an exercise perspective, neurotransmitters such as norepinephrine, epinephrine, dopamine (catecholamine's), serotonin and histamine are imperative in brain and hence, bodily functions (Purves et al., 2004; McArdle, Katch, & Katch, 2006; Boecker et al., 2012). Acetylcholine is equally important, as it modulates vagus and cardiac nerve excitation, as well as motor coordination at a musculoskeletal level (Purves et al., 2004)

Proposed by Terry McMorris, this model states that immediately before and during exercise, the hypothalamus and brainstem activate the sympathoadrenal system and hypothalamic-pituitary-adrenal axis. In response, the sympathoadrenal system increases brain and peripheral concentrations of catecholamine's, improving arousal (McMorris, 2009). The onset of exercise triggers the release of cortisol via hypothalamic-pituitary-adrenal axis which modulates arousal by limiting the synthesis of corticotrophin releasing hormone and adrenocorticotropin hormone (Lambourne & Tomporowski, 2010). Progression of exercise or increasing the intensity then facilitates the release of epinephrine and norepinephrine into the blood, which regulate cardiorespiratory responses and promote glycolysis or lipolysis (intensity and duration dependent). The continual sensory feedback from the autonomic nervous system to the brain, particularly the hypothalamus, facilitates further activation of the sympathoadrenal pathway, and in particular the release of epinephrine and norepinephrine into the noradrenergic and dopaminergic pathways in the brain (McMorris, 2009). These pathways are important for the activation of cognitive and emotional brain regions which promote movement, attentional control and arousal (McMorris, 2009). With further increases in intensity or duration of exercise, cortisol can no longer modulate the synthesis of these hormones, arousal increases and resultantly, limbic system activation also increases (McMorris, 2009). The result is decreased activation of cognitive centres within the brain, particularly the prefrontal cortex.

The model predicts that with optimal levels of physiological arousal, the corresponding norepinephrine and dopamine concentrations will influence the brain networks responsible for the facilitation of information processing and improve cognitive performance (McMorris, 2009; Lambourne & Tomporowski, 2010; McMorris et al., 2011;). However, further increases in activation (strenuous exercise) will increase the neural noise, resulting in a performance decrement (McMorris et al., 2011). It is suggested that when a good signal-to-noise ratio is achieved, improvements in stimulus encoding, decisional processes, and response mobilisation occur (Lambourne & Tomporowski, 2010).

2.8 Fatigue

Fatigue is a sensation that occurs during daily living and is a limiting factor in sustained mental and physical performance (Pinniger, Steele & Groeller, 1999). The causes of fatigue are complex and multifaceted where presentation can occur both centrally (within the nervous system) and peripherally (in skeletal muscles themselves) (Welsh, Davis, Burke & Williams, 2002; Greig et al., 2007). Further complicating this phenomenon, its assessment and definition is that fact that fatigue is subjective in nature. Therefore, a multitude of definitions describe fatigue with no single definition accepted by researchers. An appropriate definition for the current study describes fatigue as, “a state of an organism’s muscles, viscera or central nervous system, in which prior physical activity and/or mental processing, in the absence of sufficient rest, results in insufficient cellular capacity or system wide energy to maintain the original level of activity and/or processing by using normal resources” (Job & Dalziel, 2001, p 469). Further definitions describe fatigue as a sense of exhaustion, lack of perceived energy or increased tiredness (Skurvydas, Brazaitis, Andrejeva, Mickeviciene & Streckis, 2011). An integrated definition describes fatigue as a phenomenon that develops in all cognate areas of sport and exercise, which causes a reduction in physiological and psychological performance parameters, or both (Enoka, 1996; MacIntosh & Rassier, 2002).

These definitions describe a phenomenon that is context dependent where, often, the nature of activity will dictate the severity of fatigue (Enoka, 1995; Welsh et al., 2002; Girard, Lattier, Maffiuletti, Micallef & Millet, 2008). From a sports context, the following factors have profound effects on the time course and type of associated fatigue (Baechle & Earle, 2008);

(i) differences in muscle actions (eccentric vs. concentric),
(ii) activity profiles (repeated sprints vs. endurance vs. strength training),
(iii) exercise intensities,
(iv) duration of activity, and
(v) recovery ratios.

The corresponding symptoms are also context-dependent and may include; perceived pain, decreased muscular power, reduced endurance capacity, reduced motor function, reduced motor control, lapses in concentration and tiredness (Enoka, 1995; MacIntosh & Rassier, 2002; Girard et al., 2008). In self-paced and constant-rate work bouts, it is important to note that fatigue is volitional, but is mediated by a number of factors (Tucker, 2009). These include but are not limited to; environmental conditions and their subsequent effect on body temperature, the oxygen content of the inspired air as well as the substrate availability during the exercise (Tucker & Noakes, 2009). Therefore, Noakes, St Clair Gibson & Lambert (2005) contend that fatigue is better interpreted as a subjective sensory perception that results from complex integrations of physiological, biomechanical, and other sensory feedback from the periphery. This means that individual-specific psychological factors like motivation, mental toughness and perceptions of effort are crucial in mediating performance; and often these are the major differences between elite and novice athletes (Marcora, Staiano & Manning, 2009; Marcora & Staiano, 2010; Pageaux, Marcora & Lepers, 2013).

For the purpose of this investigation, cognitive fatigue and neuromuscular fatigue are the most likely types of fatigue to occur. Cognitive fatigue (or impaired information processing), is defined as a failure to sustain attention and to maintain optimal performance in tasks that are dependent on self-motivation (Holtzer, Shuman, Mahoney, Lipton & Verghese, 2012). Conversely, neuromuscular fatigue is defined as, a reversible, time-dependent reduction in both the force-generating ability and power output of a muscle (St Clair Gibson, Baden, Lambert, Lambert, Harley et al., 2003; Girard et al., 2008). Neuromuscular fatigue may result from peripheral changes at the level of the muscle or when the central nervous system fails to drive the motor neurons adequately (Gandevia, 2001): thus fatigue of this nature could be mediated both centrally and peripherally (Pinniger et al., 1999; Noakes, 2000; St Clair Gibson et al., 2003; Amann Eldridge, Lovering, Stickland, Pegelow & Dempsey, 2006; Crewe, Tucker, & Noakes, 2008; Barbieri, dos Santos, Vitório, van Dieën & Gobbi, 2013).

Central neuromuscular fatigue has been described by the following characteristics (Kay, St Clair Gibson, Mitchell, Lambert & Noakes, 2000; Gandevia, 2001; St Clair Gibson & Noakes, 2004; Girard et al., 2008);

i. located proximally to the neuromuscular junction,
ii. a reduction in neural drive or motor command to the muscle, resulting in a decline in force or tension development, and
iii. a progressive failure of voluntary muscle activation, associated with the slowing of motor unit firing rates, induced by a form of activity.

Conversely, peripheral neuromuscular fatigue is characterised by;

i. located distal to the neuromuscular junction,
ii. a decrease in the force generating capacity of skeletal muscle, and
iii. attributed to action potential failure, excitation contraction coupling failure, or impairment of cross-bridge cycling in the presence of unchanged or increased neural drive.

In a cognitively demanding task like batting, it is hypothesised that the resistance to the physical and cognitive sensations of fatigue and the ability to sustain attentive information processing will contribute to superior performance.

The multifaceted nature of fatigue has led biomechanists, psychologists and physiologists to conceptualise fatigue differently. Resultantly, there are a number of models have been theorised to explain the specific processes underlying fatigue and how these models limit optimal performance (Abbiss & Laursen, 2005; Noakes et al., 2005; Tucker, 2009; Tucker & Noakes, 2009). The models are based from either a peripheral or central perspective, and as such the mechanism of fatigue would fit accordingly.

2.8.1 Peripherally Mediated Models

(i) Cardiovascular/Anaerobic Model

Based on the works of A. V. Hill (Hill, Long & Lupton, 1924a; 1924b), the model proposes that fatigue is facilitated by limitations in cardiac output, and as a result, blood flow to the exercising muscles is reduced. This model predicts that an athletes maximum capacity for exercise, is determined by the capacity of the heart to pump blood and oxygen to exercising muscles (Noakes, 2000). Relatedly, a reduced ability of the cardiovascular system to remove waste products from exercising muscle is inherent in this model (Abbiss & Laursen, 2005). The corresponding reduction in oxygen at a muscular level means that the oxygen demand exceeds supply: this induces anaerobic metabolism; promotes metabolite accumulation which alters muscular contractile function and negatively influences performance (Noakes, 2000; Noakes & Durandt, 2000).

(ii) Energy Supply/Energy Depletion Model

A subtle extension of the cardiovascular model, this model suggests that substrate availability and utilisation are at the centre of performance regulation. Quite simply, the energy supply model proposes that maximal performance is determined by the ability of the athlete's metabolic systems to produce ATP (i.e. phosphocreatine system, oxygen-independent glycolysis, aerobic glycolysis and aerobic lipolysis) (Noakes & Durandt, 2000; Noakes, 2000; Abbiss & Laursen, 2005). The model predicts that superior performance can be explained by a greater capacity to generate ATP via the appropriate pathway inherent to that sport. The energy depletion model, which is modelled for prolonged exercise, suggests that when all available substrates are depleted, performance is likely to deteriorate (Noakes, 2000; Abbiss & Laursen, 2005).

(iii) Biomechanical Model

This model proposes that efficiency within a muscle is a major proponent of improved performance during exercise, and that the economy of the whole system is paramount to successful performance (Noakes, 2000; Abbiss & Laursen, 2005). It suggests that an enhanced capacity to store elastic energy will require less torque to overcome a corresponding load. As such performance will be promoted by; (i) reducing the VO_2 required to sustain a given workload, (ii) the rate of substrate utilisation, (iii) the rate of metabolite accumulation, and (iv) the rate of heat accumulation (Noakes, 2000; Abbiss & Laursen, 2005). Consequently, athletes who lack this ability, or who perform uneconomically may suffer early onset fatigue and reduced performance.

(iv) The Neuromuscular Propagation Failure Theory

This theory contends that fatigue occurs at the level of the sarcolemma or alpha motor neuron, and is characterised by a diminished response of the muscle to the corresponding electrical stimulus (action potential) (Abbiss & Laursen, 2005).

(v) The Muscle-Power Model

This model predicts that fatigue occurs within the muscle fibres where excitation-contraction coupling failure may be the underlying mechanism. This theory proposes that the contractile capacity of skeletal musculature limits performance (Noakes, 2000).

2.8.2 Centrally Mediated Models

(i) Central Activation Failure Theory

While the cardiovascular model is the most widely accepted mechanism of fatigue during exercise, it is considered to have many flaws[1] (Noakes, Peltonen, & Rusko, 2001). The principal flaw, as postulated by Noakes (2000), was that before oxygen supply to exercising muscles is limited, the heart would experience an ischemic state of its own, resulting in catastrophic fatigue. This flaw led to the formation of 'The Central

---

[1] For a comprehensive review of this model and the flaws associated with the initial cardiovascular/ anaerobic model of fatigue, please consult (Noakes, 2000).

Governor Model' proposed by Professor Timothy Noakes. While the model has a strong grounding from A. V. Hills work, it suggests that the brain (and not the heart) is the regulator of human performance: and in no circumstance will the brain allow for catastrophic failure to take place when performing maximal exercise (Noakes et al., 2001, 2005). In this model, the brain will reduce efferent output to active motor units and hence, the recruited muscle mass. This will, in turn, decrease the workload of the muscles and the stress on the heart (Noakes et al., 2001, 2005).

One suggestion is that changes in neurotransmitter concentrations within the brain alter the density of neural impulses reaching exercising skeletal muscle, thereby reducing recruitment (Noakes, 2000). From a thermoregulatory perspective, this model suggests that once a critical core body temperature is attained, exercise is reduced or terminated (Abbiss & Laursen, 2005). Centrally, the hypothalamus receives afferent information from peripheral receptors regarding the current state of the system. The hypothalamus then regulates central neural drive and sympathetic stimulation processes during exercise to reduce heat accumulation (Abbiss & Laursen, 2005). It is thought that increases in core body, muscle and skin temperatures increase the demands on other physiological systems which may drive fatigue responses in other models (Abbiss & Laursen, 2005).

The Complex Systems Model is an extension of Noakes' Central Governor Model. It predicts that no single linear model can explain muscle fatigue in isolation, but rather, fatigue can only be explained through the complex interaction of a number of the models previously proposed (Abbiss & Laursen, 2005; St Clair Gibson & Noakes, 2004; Lambert, St Clair Gibson, & Noakes, 2005). It suggests that muscular performance is continually regulated by a 'governor mechanism' within the brain. The mechanism though which it acts is feed-forward control in response to afferent feedback from multiple central and peripheral sensors (Lambert et al., 2005; Noakes et al., 2005; St Clair Gibson & Noakes, 2004). This 'governor' then alters skeletal muscle output accordingly. As such, each of the different homeostatic mechanisms interacts with the goal of maintaining whole-body homeostasis.

(ii) The Anticipatory Feedback Model

This model proposes that conscious control or effort regulation is paramount in sustaining performance (Abbiss & Laursen, 2005; Noakes, 2000). Recently, an athlete's ratings of perceived exertion (RPE) are suggested to influence performance regulation (Tucker, 2009), a theory supported by a number of researchers (Crewe, Tucker, & Noakes, 2008; Tucker & Noakes, 2009; Marcora, 2010; Marcora & Staiano, 2010; Smits, Pepping, & Hettinga, 2014; Pageaux, Marcora, Rozand & Lepers, 2015). The Anticipatory Feedback Model suggests that work rate is regulated by a combination of feedback integration and anticipatory forecasting. To achieve this, the model suggests that: (i) previous experience, (ii) teleoanticipation of exercise duration/distance, and (iii) physiological feedback are used to regulate performance (Tucker, 2009). In short, before the onset of exercise the brain creates a template RPE which is based on previous experience, expected duration of exercise and pre-exercise physiological inputs. During exercise and to avoid premature exercise termination, the brain integrates afferent feedback from various physiological systems (conscious RPE) to regulate output. Therefore, conscious RPE is continually monitored and output mediated to ensure it does not exceed the template RPE. (Tucker, 2009). Tucker contends that the model prevents the exercising athlete from continuing exercise and causing bodily harm, through RPE's responsibility for the volitional decision to terminate exercise. Further, it mediates exercise intensity to ensure that the known exercise bout can be completed safely, but also optimally.

(iii) The Psychobiological Model

While heavily seated within the neuromuscular fatigue model, this model proposes that endurance performance is regulated by psychological as well as physiological models (Marcora, 2008; Marcora & Staiano, 2010; De Morree & Marcora, 2013; Pageaux, Marcora, & Lepers, 2013; Pageaux, 2014). It suggests that a lack of motivation or enthusiasm in performance may result in a conscious reduction in neuromuscular function, causing a decrease in motor activation and the termination of exercise (Abbiss & Laursen, 2005). More recently its application has also been verified in self-paced exercise (De Morree & Marcora, 2013; Pageaux, 2014; Pageaux, Lepers, Dietz & Marcora, 2014). The model bares similarities to the anticipatory and the central governor models, in that performance is regulated by effort; however, where it is different is that does not suggest that a subconscious area of the brain regulates performance through teleoanticipation (Marcora, 2008). Rather, it holds that perception of 'fatigue' does not stem from afferent feedback, but rather, from central processing of the corollary discharge associated with the central motor command (Pageaux, 2014). The model proposes that performance is regulated by five factors: (i) perception of effort, (ii) motivation, (iii) knowledge of the distance to cover, (iv) knowledge of the remaining length and exercise time, and (v) previous experience/ memory of perceptions of effort during exercise of varying intensity and duration. Pageaux (2014) argues that the key determinant of this model is the individual's perception of effort. When this perception reaches a level that is too high and motivation is insufficient, the athlete will alter pace to ensure the exercise bout is completed optimally.

2.9 The Art of Batting: What Needs Further Explanation?

No study has assessed the cognitive demands required while batting, nor the domain-related changes in cognition during batting. The effects of prolonged-intermittent activity and accompanying fatigue of information processing, attention allocation and effort regulation also need further elucidation. Further, the implication of this particular fatigue mechanism on batting performance also needs to be established. While it is important to understand the intricacies in each of these topics, the investigation of these in a holistic manner is the only way that we can completely understand batting-related cognitive performance. For this goal to be realised, the allocation of attention at each cognitive domain and the performance-related changes within each domain need to be understood. This may allow sports scientists to better understand how the batting-related cognitive domains are affected by activity of this nature. This will need to be dealt with at each level of cognitive processing, where performance at all stages of information processing is measured. Only when this information is available and provided holistically can training and conditioning practices be augmented to improve batting and performance during competition.

CHAPTER III - METHODOLOGY

A fundamental challenge in sport and exercise science is designing methodologies that encompass control as well as ecological validity. With this in mind, an applied method stimulated the physiological and mechanical demands required in the scoring of a one-day century, while incorporating aspects of competition to promote ecological validity. The study was structured in three phases, each designed to assess performance with the same methodology. *Phase 1* was essentially a large pilot study that informed the methodology for the subsequent stages. In *phase 2* and *3* the methodology and sample implemented was identical and served to test the reliability of the method. The major differences between the phases were the frequency of cognitive assessment and the samples recruited. In *phase 1*, schoolboy batters were recruited and cognitive performance was assessed on five occasions. In contrast, a cohort of academy batters were recruited for *phase 2* and *3*. These phases formed a repeated measures, test-retest investigation where cognitive performance was only assessed on three occasions. Further detail will be provided in the subsequent sections. Unless stated otherwise, all the techniques, procedures and dependent measures were the same in *phase 1*, 2 and *3*. Please note that the terms '*phase 2*' and '*phase 3*' are synonymous with '*test'* and '*retest'*

3.1 Ethical Considerations

Before the commencement of any data collection the Rhodes University Ethical Standards Committee for research involving human participants approved all procedures of the protocol (RU-HSD-14-12-0002).

3.1.1 Informed Consent

Before the onset of testing, each batter was required to sign informed consent (Appendix A: 10.2.4). However, due to the nature of the experimentation and the fact that minors would form part of *phase 1*, specialised consent was obtained by their respective schools and parents. Once consent from these parties was established, verbal assent was obtained from each minor. This confirmed that each participant was familiar with the testing procedures and inherent risks associated with their participation in the study.

3.1.2 Privacy and Anonymity of Results

Information obtained during experimentation was kept confidential and at no stage or time was any batters information publicised. The data that was collected during the experimental protocol was used only for statistical analyses. Furthermore, one copy of the data was kept in the Human Kinetics and Ergonomics department to be used for teaching or research purposes. However, if data was used for teaching purposes, anonymity was ensured by replacing participant names with a unique participant testing code.

3.2 Research Design

A repeated measures laboratory-based design was employed, where batting performance of top order batters was assessed. The experimental design simulated (as far as possible) the physical, physiological and cognitive demands of batting when scoring a century (100 runs). Continuous sampling of dependent variables provided comprehensive quantitative data regarding prolonged intermittent activity. A repeated measures laboratory design was also utilised in *phase 2* and *3*.

3.2.1 Sample Characteristics

As far as possible, skill level was standardised so that batting-related effects could be attributed to the protocol and not to differences in expertise, so as to improve the reliability of results.

Phase 1: 15 Experienced[2] batters from three schools in the Eastern Cape Province of South Africa were recruited for *phase 1*.

Phase 2 and 3: 16 Academy cricketers[3] from the TUKS ASSUPOL Cricket Academy in the Gauteng Province of South Africa were recruited for *phase 2* and *3*.

Inclusion criteria were the same for all batters and were: (i) that batters must bat in the top 5 of their teams' batting line-up, (ii) that players must not have been injured in the six months

---

[2] Refers to a batter that has had at least five years of hard ball playing experience and currently plays for the First XI, Second XI or Third XI team for their respective school/academy.

[3] Academy refers to amateur batters who were contracted to the TUKS ASSUPOL cricket academy and who were playing in their amateur teams (Third, Fourth, Fifth and Sixth XI).

before the study, and (iii) that a detailed medical history was provided. The characteristics of the samples utilised are presented in Table V and Table VI.

Table V: Participant characteristics of schoolboy batters, *n* = 15 (RHR = reference heart rate, BMI = body mass index, Body Fat % = Skinfolds - Jackson and Pollock sum of seven method).

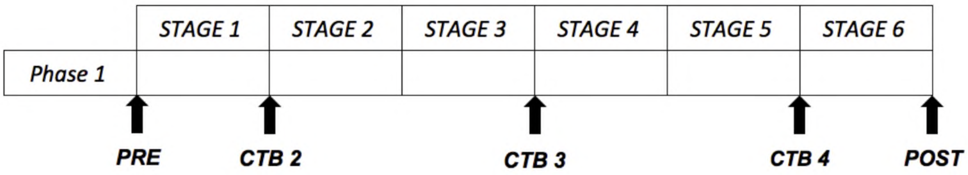
	AGE	***RHR***	***STATURE***	***MASS***	***BMI***	***BODY FAT***
	years	bt.min^{-1}	m	kg	kg/m^2	%
MEAN ± SD	17.7 ± 0.96	65 ± 10.34	1.75 ± 0.06	76.52 ± 11.29	24.98 ± 2.66	8.43 ± 4.61
CV	6%	16%	3%	15%	11%	55%

Table VI: Participant characteristics of academy cricketers, *n* = 16 (RHR = reference heart rate, BMI = body mass index, Body Fat % = Skinfolds - Jackson and Pollock sum of seven method).

	AGE	***RHR***	***STATURE***	***MASS***	***BMI***	***BODY FAT***
	years	bt.min^{-1}	m	kg	kg/m^2	%
MEAN ± SD	19.13 ± 1.02	70 ± 7.89	1.76 ± 0.08	75.45 ± 8.40	24.28 ± 1.99	9.27 ± 3.15
CV	5%	11%	4%	11%	8%	34%

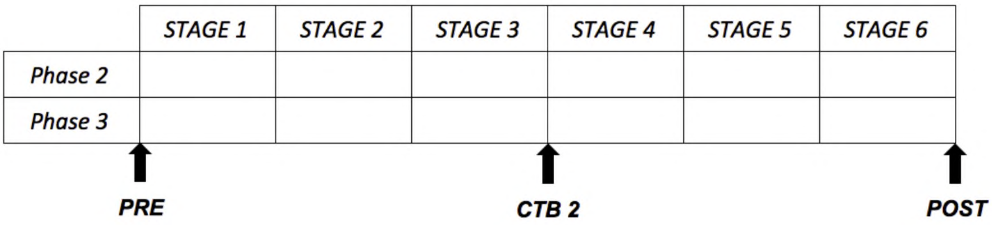
In *phase 1* batters attended one experimental condition comprising six batting-related stages interspersed with five cognitive test batteries (Table VII). The high frequency of cognitive data collection allowed performance to be assessed at *pre-test*, *during* and *post-test*. At the halfway point (after the third cognitive test battery [*CTB 3*]) a drinks break was implemented where all batters consumed 250ml of Energade (345 kJ; 39 CHO). This was implemented to prevent hypoglycaemia. No other substrates were permitted during experimentation.

Table VII: *Phase 1* experimental design matrix.



Phase 2 and *3* were conducted approximately six months after *phase 1*, where a different sample of players was recruited. Academy batters attended two experimental sessions (session 1 = *phase 2*; session 2 = *phase 3*) in a repeated-measures design. The method here was the same as *phase 1*, however, one fundamental change was implemented; the frequency of cognitive assessment (Table VIII). The justification for this was the uncharacteristic rest that accumulated from the cognitive three test batteries implemented during batting. In limited overs cricket, prolonged rest periods (i.e. > 15 minutes) are only taken at the change of an innings or once the game is complete. Therefore, *CTB 2* and *CTB 4* were removed to make the simulation more representative of competition. Water was the only substrate permitted and was done so on an *ad libitum* basis. The amount of water consumed was measured at the end of each session.

Table VIII: *Phase 2* and *3* experimental design matrix.



	STAGE 1	*STAGE 2*	*STAGE 3*	*STAGE 4*	*STAGE 5*	*STAGE 6*
Phase 2						
Phase 3						

In each phase, multiple dependent variables were sampled to gain a holistic view of batting performance, these included; cognitive performance, batting performance (bat-ball accuracy), physical performance (sprint times, vertical jump height), physiological responses (heart rate and heart rate variability) and perceptual responses (central and local ratings of perceived exertion).

3.3 Independent Test Protocol

3.3.1 BATEX

The BATEX simulation was designed specifically to replicate the match demands of high-intensity prolonged batting (Houghton et al., 2011a). The protocol lasts 30 overs (6 balls/over), comprises six 21-minute stages (three low- and three high-intensity) and is approximately 2 h 20 min in duration. The structure and design of this protocol is represented in Table IX. BATEX is administered via an audible track (Audacity, v.1.2.6 and Verbose text to speech, v.1.13), which instructs the researcher and athlete what is required. At the start of each over, the track details the runs required (17.68 m shuttles) and how the runs must be obtained (i.e. stage 1, over 3: two singles and a double shuttle – totalling 4 shuttles). Also at the start of each over, the principal researcher reminded players of the field setting. This field setting was consistent in all phases and for all batters. Batters completed the runs in any order but were encouraged to match the runs with the shot played and the field setting. The primary requirement was that all runs needed to be completed by the end of the over. A siren instructed the researcher to place each ball into the bowling machine (set to deliver the ball at approximately 105 km.h^{-1}). While the use of a bowling machine may reduce the overall cognitive demands of batting and is a limitation of the current design, logistically this was the most feasible option for delivering the high frequency of deliveries (180) during experimentation. A 35-second period between deliveries, allowed for recovery and the simulation of the bowler returning to his mark. Seventy five seconds were allocated between overs and 120 seconds between stages.

Table IX: Individual and total workloads of the BATEX simulation (adapted from Houghton et al., 2011).

	Runs completed in each over of BATEX					**Totals**	
BATEX Stages	**Over 1**	**Over 2**	**Over 3**	**Over 4**	**Over 5**	**Runs**	**Shuttles**
1. Building momentum	1,1	No runs	1,1,2	1,4	1,4	**16**	**11**
2. Taking initiative	1,1	1,1,2	1,1,4	1,1,2	1,1,4	**22**	**17**
3. Fighting Back	No runs	1	1,4	2,3	1,4	**16**	**11**
4. Power play	1,1,4	1,1,2	1,1,4	1,1,2,3	1,1,4	**29**	**21.5**
5. Mainitaining tempo	1,3	1,1,2	1,1,4	1,1,2	1,1,4	**24**	**19**
6. Closing out the innings	1,1,3,4	1,1,2,4	1,1,4,1	1,1,2	1,1,2,4	**36**	**26**
Overall run breakdown:	**1's = 49**	**2's = 11**	**3's = 4**	**4's = 15**	**34: Turns**	**143**	**105.5**

Running intensity in stages one, three and five was at a ‘self-selected cruise pace’, with, stages two, four and six requiring maximal sprint speed. In attempting maximum sprinting speeds, each participant was verbally encouraged by the principal researchers. As far as possible, encouragement was standardised across sessions. When required to run for a boundary (4), the batter ran one-and-a-half shuttles. This simulated the batter running the single and then decelerating after the turn (a game-based situation when the batter realises that the ball has crossed the boundary rope). Additionally, batters were requested to adopt the correct technique of turning at the crease; that is, turning to the side where the ball was struck while simultaneously watching the ball. The simulation comprises a total of 143 runs scored and 105.5 shuttles. The basis for this is to simulate partnerships, where batters must run not only their own runs, but also those of their batting partner. The workload and intensity required in each stage are theoretical phases of play and based on typical running-between-the-wickets patterns. These were established from the following analyses: (i) team innings during the 2007 and 2009 Twenty20 World Cups, (ii) the 2003 and 2007 One-Day International World Cups, and (iii) the home and away Test match series between Australia and South Africa (Houghton et al., 2011a)[4].

The protocol was followed exactly as instructed by the audible track and to the recommendations of Houghton et al. (2011a). The only deviations from their protocol, was for the assessment of cognitive functioning. *Phase 1* had three additional 20-minute intermissions (after the 5th, 15th and 25th overs), while *phase 2* and *3* had only one additional intermission (after the 15th over).

3.3.2 Selection of Ball Speed and Ball Characteristics

The ball speed, line and length of the delivery were controlled with a bowling machine: Jugs Express (Tualatin, Oregon). This particular machine was selected on the following criteria; consistency in deliveries, adjustability (speed and ball types [swing, spin, line and length]) and being 'bat friendly'. While the use of a bowling machine does reduce the variability in delivery types and hence the ecological validity of the test protocol, this ball-projection method was implemented to increase safety and consistency. From a safety perspective, ball-projection was selected to control the speed of the delivery to ensure 'stray deliveries' were avoided. The bowling machine was set to deliver each ball on a consistent line and length that would encourage a front foot drive by the batters. Furthermore, this method of delivery prolonged the functionality of the batting accuracy hardware (section 3.4.3) so that this was not compromised. Pote (2013) conducted a series of pilot studies on the accuracy hardware and determined that 105 $km.h^{-1}$ was the maximum speed that could be used during experimentation. Speeds in excess of this compromised the correct functioning of the

---

[4] For a comprehensive review of the BATEX protocol and the foundations of its development please consult Houghton *et al*. (2011a).

switch matrix. Loram et al. (2005) measured the determinants of ball release speed in South African amateur bowlers and observed an average speed of 29.2 (±1.8) $m.s^{-1}$ in high school players (98.64 - 111.6 $km.h^{-1}$). Consequently, the utilisation of this speed range is deemed appropriate for schoolboy and academy batters. With the above in mind, 105 km^{-1} was implemented as the ball-projection speed.

Logistically, it was not feasible for one bowler to bowl 30 consecutive overs in the protocol. This sort of procedure would result in fatigue of the bowler and inconsistencies in the delivery of the ball. Further, it would not be feasible to use multiple bowlers in this protocol, as variability in bowling as well as in speed may increase ‘stray deliveries’ and the risk of damage to the batting accuracy hardware.

3.3.3 Total Test Battery Duration

Total experimental duration approximated four hours. The composition was as follows, 1 hr. and 20 min for cognitive assessment (5 x 20 min sessions) 2 hr. 20 min for the BATEX protocol and a 20-minute period for a sufficient warm up before experimentation. Session duration of *phase 2* and *3* was similar to *phase 1*. With the addition of the vertical jump test protocol (*pre* and *post-test*) and the reduced number of cognitive test batteries, *phase 2* and *3* were approximately 20 min shorter.

3.4 Dependent Variables

3.4.1 Cognitive Performance

The CogState[5] Brief Test Battery (Melbourne, Australia) was selected because of its scientific validation (Falleti et al 2006; Pietrzak, Cohen, & Snyder, 2007; Pietrzak et al., 2008; Maruff et al., 2009), its applicability in assessing cognitive performance in a variety of domains, its sensitivity to a number of ailments and impairments (Luft et al., 2009; Steinberg et al., 2014) and for the limited practice effects associated with repeated measures studies (Collie et al., 2001; Falleti et al., 2006). Furthermore, given the high visual demands required in batting, this battery was selected for its visually oriented setup, where tasks require processing from both the visual and motor systems. The computerized nature of the battery,

---

[5] For an in-depth review of the cognitive assessments available from CogState Ltd., please consult - URL:http://cogstate.com/clinical-trials/cogstate-system/test-examples/#.VNCS3EIeW-J)

when compared to traditional 'pencil paper' assessments, provided enhanced reliability (improved accuracy in measurement) while simultaneously reducing test administration time – an important criterion in replicating game demands. This specific battery of tests was short in duration (~16 min) and had the ability to assess multiple cognitive domains by means of processing speed and response accuracy. The cognitive domains assessed included: (i) psychomotor function, (ii) visual attention/vigilance, (iii) visual learning and memory, (iv) attention and working memory, and (v) executive functions (spatial problem solving).

While longer, more complete test batteries (43.5 min) do exist; these batteries were excluded for two reasons. (i) the nature of cricket and associated experimentation does not allow for a lengthy break from activity, and (ii) the total duration of the protocol and hence the time required from each participant would be unrealistic. Furthermore, when scoring a century, prolonged rest breaks are uncommon and the general intensity of play is moderate to high. Therefore, the full CogState test battery would have reduced the ecological validity of BATEX and the collected results.

The test battery comprised five game-based (playing cards) tasks to assess cognitive performance. Each task was preceded with simple textual instructions, followed by an initial practice bout and then, the scored component. An Acer Extensa (5635) Laptop computer (New Taipei, Taiwan) was used to run the battery and a Logitech (M35) infrared wireless mouse (Lausanne, Switzerland) was the selected input modality (controlled by the dominant hand). The visuomotor requirements of each task remain identical; however, equivalent forms of each task are generated based on random stimulus selection, binary responses and alternating inter-stimulus intervals (1500–2000 ms inter-stimulus interval) (Darby et al., 2014). The duration of each task was batter-specific, where a certain criteria needed to be met before the task was completed (i.e. *detection* task = 35 correct responses). The largest limitation of this battery is that task order could not be permutated. The tasks selected and the order of their appearance was as follows.

3.4.1.1 Groton Maze-Learning Test

Duration: ~5 minutes *Domain: Executive Function*

The participant was shown a 10 x 10 grid of tiles through which they were required to find a hidden pathway (Figure 3). The start and end of the path are indicated by a blue square (top left corner) and bulls eye (bottom right corner). Participants were required to find and remember the hidden path by selecting (left mouse button click) a block. Moving right and left or up and down, the participant had to find the next correct block (indicated by a green tick) before a second selection was made. In the event that an incorrect selection was made (indicated by a red cross) the participant had to return to the last correct location and continue the path in a different direction. This process must be repeated as fast as possible until the endpoint is reached. Once the path had been found the participant would perform an additional four trials of the same pathway, attempting each time, to reduce error rates and improve speed.

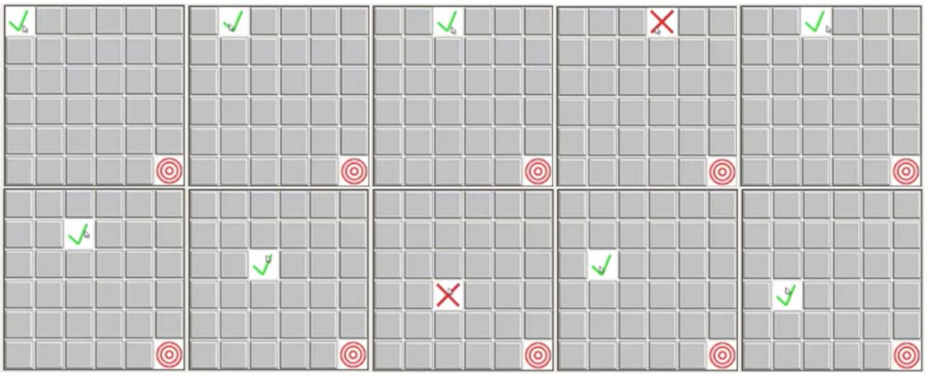


Figure 3: *Groton maze-learning* task

Participants were required to adhere to two rules; they may not move diagonally, and they may not move backwards along the path. The cognitive domain assessed in this task was executive functions and included the following domains; processing speed, spatial learning efficiency, and error monitoring (Pietrzak et al., 2007). The primary outcome measure was the total number of errors made in the five attempts. A lower error rate represented improved executive function. Future reference to this task is made with the term '*maze*' task.

3.4.1.2 Detection Task

Duration: ~2 minutes *Domain: Psychomotor Function*

The first card-based task presented a standard deck of cards face-down on the display (Figure 4). Participants were required to answer the question, “Has the card turned over?”. Once the card had been turned face-up, the critical response required of each batter was a right click of the mouse button. This task assessed psychomotor function or speed of processing. Response time (log^{10}- transformed correct response times) was the primary outcome measure, where a faster time indicated improved psychomotor function.

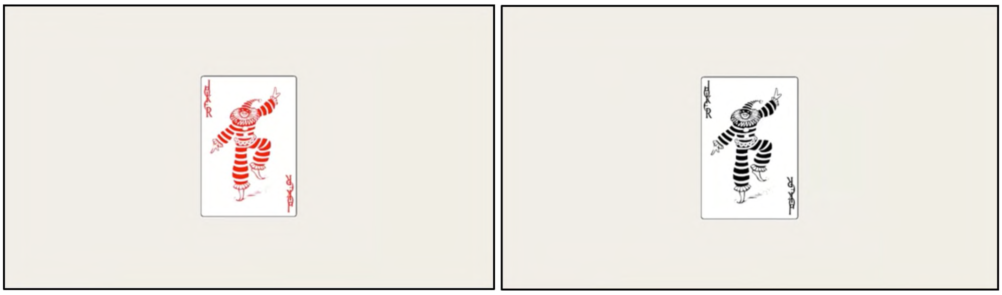


Figure 4: Illustration of the *detection* task

3.4.1.3 Identification Task

Duration: ~2 minutes *Domain: Vigilance*

Participants responded to the question “Is the card red?” (Figure 5). Modality input had a possibility of two responses; “yes” or “no” (right and left mouse button click, respectively). The increasing decision-making component requires heightened visual attention and as such, the objective was to respond as quickly as possible with the least number of errors. Response time (log^{10}- transformed correct response times) was the primary outcome measure recorded, with a reduced time indicating improved visual attention.

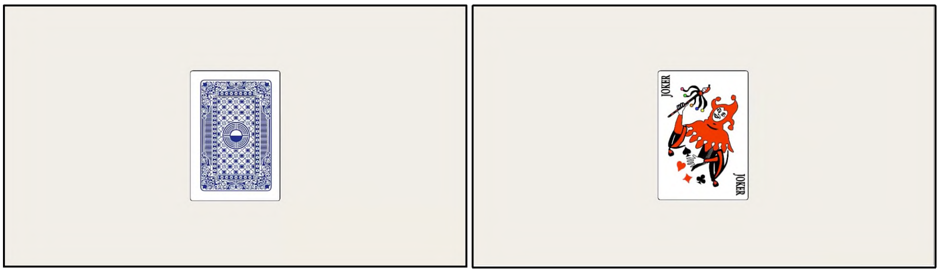


Figure 5: The *identification* task

3.4.1.4 One Card-learning Task

Duration: ~5 minutes *Domain: Visual Learning and Memory*

In this task, each time a card is revealed the participant must assess whether or not the same card (number and suit) has previously been shown in the deck, answering the question

"Has the card been seen before?". The critical response for this task required either a right ("yes") or left ("no") mouse click. As such, the first response in all trials is always "no" (left click). This task assessed speed and accuracy; however, the primary outcome variable was response accuracy (number of correct responses divided by the total number of responses). A higher accuracy rate represented improved visual learning and memory.

3.4.1.5 One-back Task

Duration: ~2 minutes *Domain: Attention and Working Memory*

The final task asks the question, "Is the previous card the same?". The batter was required to decide whether or not the current card is identical to the previous card (Figure 6). As with the previous task, the initial response was always "no". When the face-up card was the same as the last, the participant responded with a right mouse click ("yes"). In Figure 6 the correct response sequence would be "no", "yes", "no", "no". The primary outcome measure was response accuracy, with a higher score demonstrating improved working memory.

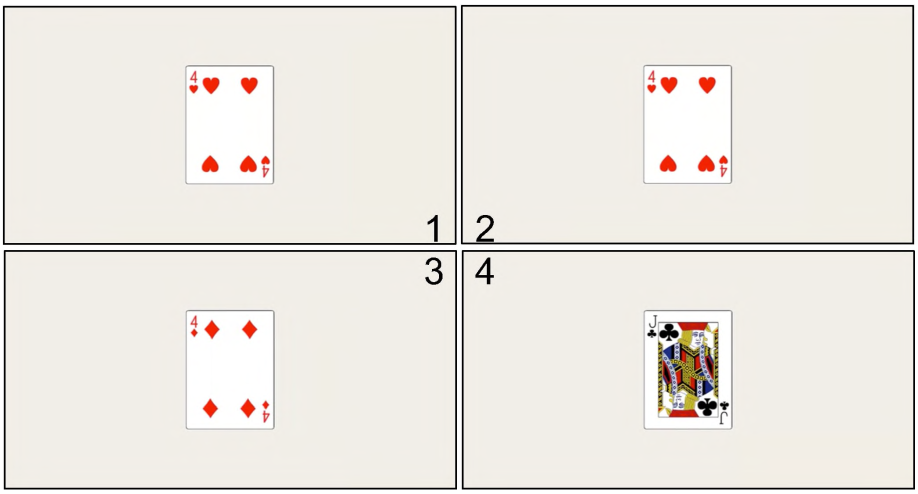


Figure 6: The *one back* task (Sequence 1 - 4)

3.4.2 Physical Performance

3.4.2.1 Repeat Sprint Ability: Muscular Endurance

Sprint times were measured during maximal stages (2, 4 and 6) using a system custom built by the Physics and Electronics Department from Rhodes University, Grahamstown, South Africa. This system has been used and validated in previous studies from our department (King, Christie, & Todd, 2002; Pote & Christie, 2015). Two infrared LED timing gates activated and deactivated a timing box, allowing measurement of all respective shuttles. The first gate was positioned at the level of the player's torso 2 m from the batters 'popping crease', with the second positioned 2 m before the opposite crease. Sprint times were, therefore, assessed between timing gates, over 13.68 m (Figure 7). Once the shot had been executed, the participant would initiate the first LED gate ($A_{1\&2}$), activating the timer. When crossing the second LED gate ($B_{1\&2}$) the timer was deactivated and the time was displayed on the output meter. In the event of a double shuttle, $B_{1\&2}$ would reactivate the timer while $A_{1\&2}$ would deactivate the timing system. The initial activation of $A_{1\&2}$ and deactivation of and $B_{1\&2}$ would time the third shuttle when a three was required.

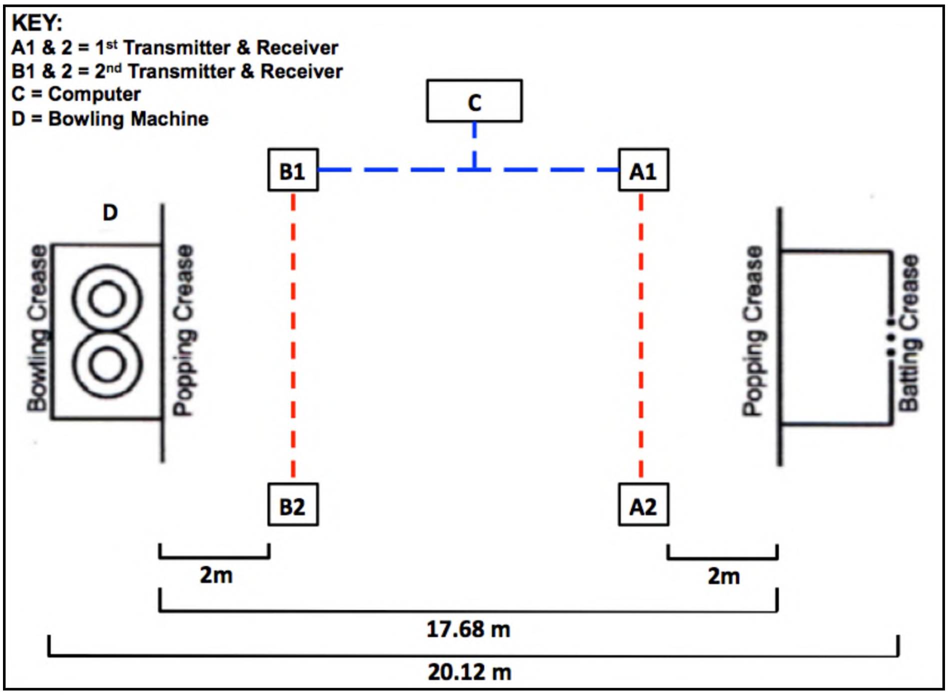


Figure 7: Sprint timing set-up.

Mean sprint times in each over for the various shuttles were calculated as the average of the completed shuttles (Equation 1).

Equation 1: Mean sprint time calculations.

$$\text{Double Shuttle} = \frac{ST\,1 + ST\,2}{2} \qquad \text{Triple Shuttle} = \frac{ST\,1 + ST\,2 + ST\,3}{3}$$

Where: ST = shuttle time

3.4.2.2 Muscular Power

Phase 2 and 3 only

SJ and CMJ heights were measured using a GameCraft jump and reach board, chalk powder and a standard 3 m steel measuring tape. Three trials of each jump were taken before and after batting, with the highest SJ and CMJ recorded as maximal vertical jump height. Jump order was permutated for *pre* and *post-test* measures in both *phase 2* and *phase 3*. Before each jump, participants placed a liberal amount of chalk on the index and middle finger of their dominant hand. Thereafter, the start position (highest point reached with the dominant middle finger while standing 0.3 m from the board, with the acromion process lined-up with the centre of the board) and inter-jump intervals (30 seconds) were established. After, participants began the jump sequences. Two trials were completed, whereafter the principal researcher measured the distance (steel measuring tape - to the nearest 0.1 mm) between the highest chalk mark and the starting position.

3.4.3 Batting Performance: Bat-Ball Interception

Phase 1 only

A fundamental requirement of successful batting is intercepting the ball with the correct timing and force to successfully penetrate a gap in the field. Interception represents a batter's ability to detect the ball, determine line and length of delivery, and program the motor system to select and to execute the necessary shot. To assess this, bat-ball accuracy (mean deviation) was measured during batting (overs 1, 5, 15, 25 and 30), where higher bat-ball accuracy would infer improved information processing. While the small number of samples (17% of deliveries) recorded can be seen as a limitation, the correct functioning of the accuracy hardware was of primary concern. For this reason, only the five overs mentioned were sampled. To maximise the number of collected samples, batters were requested to hit every delivery in each the sampling over.

Accuracy was measured using a specially designed wireless electronic accuracy device (Physics and Electronics Department from Rhodes University, Grahamstown, South Africa). This device is composed of two flexible circuit boards that were etched with a switch matrix and affixed to the 'face' of a standard short handle cricket bat. When bat-ball contact was made, these two circuit boards would make contact with one another, producing an X and Y coordinate on the switch matrix. These coordinates were then wirelessly transferred from a microcontroller (on the reverse side of the bat) to a USB module plugged into an Hewlett Packard 430s laptop computer (California, USA), which was then displayed on screen. This data was then recorded with the accuracy software and transferred to Microsoft Excel for further analysis. The impact site was recorded in millimetres of displacement from the centre of the bats 'sweet spot'[6]. For example, a ball that impacts exactly in the middle of the sweet spot will register coordinates of X:0 and Y:0. Conversely, a ball that impacts on the right-hand-side of the sweet spot and high would register (-4; +6) or a ball that was left and low would register (+4; -6). Based on the laws of Pythagoras, the distance from the centre of the bat could be calculated hence batting accuracy was recorded as mean displacement (mm).

Unfortunately the batting accuracy hardware was damaged beyond repair in the early stages of *phase 2* experimentation. Resultantly, this measure was not recorded in *phase 2* and *3*.

3.4.4 Physiological Parameters

3.4.4.1 Heart Rate

Heart rate was sampled continuously throughout the protocol and recorded at the end of each over. A Polar T34 strap (Kempele, Finland) was attached to each participant at the level of the xiphoid process and was paired with a Polar FT20 watch. To minimise shot interference, the watch was attached to the back of the batters' thigh pad. This also prevented the participant from seeing heart rate while batting.

3.4.4.2 Heart Rate Variability

Jorna (1992) states that stationarity is essential when analysing heart rate variability, where standing and physical activity have large influences on heart rate variability. As such, heart rate variability was sampled during cognitive assessment only. To facilitate continuous recording of heart rate parameters during cognitive assessments, the FT20 watch and T34 belt were paired with a Biometrics Datalogger, MWX8 (Biometrics Ltd.: Newport, United Kingdom). Both time domain (SDNN, RMSSD, PNN50 and PNN50) and frequency spectrum

---

[6] The position of this sweet spot has been correlated to the centre of the face of the bat at 160mm from the base (Mckellar, Nurick, & Stretch, 1998; Stretch et al., 2004)

components were analysed (low frequency [LF], high frequency [HF], very-low frequency [VLF], the ratio between low- and high-frequency [LF:HF] and normalised frequency data [$LF_{n.u}$ and $HF_{n.u}$]). SDNN and RMSSD were selected as the primary time domain variables, as these are the most commonly utilised domain measures (Malik et al., 1996). Low- and high-frequency spectra in raw and normalised units (n.u) were selected to represent sympathetic and parasympathetic activation and the balance between these systems (Luft et al., 2009).

Although cognitive assessment approximated 15 min, heart rate variability was assessed over a standardised period. Battery-related differences were analysed over a 14-minute period (shortest time-on-task was 14:23 mm:ss) allowing analysis of two seven minute periods. This longer time period, according to Jorna (1992), increases the reliability of the frequency spectrum results. In contrast, task-related differences were analysed for the full duration of each task. These intervals were recorded with a SANJI 1100 stopwatch and analysed appropriately. Data were reduced with an in-house data reduction tool, which applied a fast Fourier transformation to convert raw heart rate data into time-domain and frequency spectrum parameters. Data were then filtered to reduce artefacts that were in excess of 200 $bt.min^{-1}$ and lower than 40 $bt.min^{-1}$. Interval lengths of 10 and 60 seconds were used to analyse task- and battery-related differences.

3.4.4.3 Estimated Fluid Balance and Sweat Loss

Fluid loss during the protocol was calculated by observing changes in body mass (King et al., 2002). Changes in nude body mass (to the nearest 0.01 kg) were recorded before and after the batting simulation using a LifeMax electronic scale (Johannesburg, South Africa). To determine the amount of sweat accumulation within the clothing and equipment, changes in body mass with full cricket kit and clothing were also recorded before and after batting. Water was assigned a density of $1.0g.ml^{-1}$ and with the equations presented below, absolute and relative sweat loss (SL_{ABS}: Equation 2) and rate of sweat loss (SR_{ABS}: Equation 3) were calculated. Additionally, relative sweat loss and the relative rate of sweat loss for each batter were also calculated.

Equation 2: Absolute sweat loss

$$SL_{ABS}\ (l) = (BM\ pre\ - BM\ post) \times g/ml$$

Where: BM = Body Mass (kg)

Equation 3: Absolute rate of sweat loss

$$SR_{ABS}\ (l/h) = \frac{SL_{ABS}\ (l)}{duration\ (min)} \times\ 60\ min/h$$

3.4.5 Perceptual Responses

Central (cardiovascular) and local (muscular) ratings of perceived exertion (RPE) were recorded at the end of each over and stage. These were recorded to measure perceived cardiovascular and muscular strain continuously, so that it could be related to the continuous measurement of heart rate. Furthermore, this would provide information on the perceived strain of each stage of the batting simulation. During familiarisation, all participants were trained on how to interpret their cardiovascular and physical strain and to rate this strain on the rating scale. Each participant verbally acknowledged their perceived exertion when presented with a Borg 15-grade rating scale (Borg, 1982). The scale is a graded rating system, which allows perceived effort to be rated from a minimum of 6 ('very, very light') to a maximum of 20 ('very, very hard').

3.5 Controlled Variables

Although it is often difficult to control for all extraneous variables inherent in scientific experimentation, meticulous efforts were made to standardise testing conditions for each participant who participated in the study.

3.5.1 Environmental Effects

Experimentation took place in an indoor high-performance cricket facility in order to standardise environmental conditions. The premise behind the use of this environment was to control for lighting, temperature and humidity as well as the running surface – variables that often influence visual and physical performance. Temperature was controlled with the centre's air conditioning unit and was set at 23°C in all testing sessions. Although testing indoors was not fully representative of cricket match play and also reduced the ecological validity, it was necessary to allow for reproducibility of conditions between participants as well as for the study as a whole.

3.6 Instrumentation and Measurement of Variables

The following equipment was utilised to record baseline data during habituation and to monitor and measure performances changes during the batting simulation.

3.6.1 Demographic, Anthropometric and Morphological Measurements

The introduction and habituation session served as a basis for the collection of demographic data. These data included the players' cricket history as well as basic demographic data of the batters (gender, age and ethnicity). The following anthropometric measurements were obtained in the introductory session to establish the anthropometric characteristics of the sample.

3.6.1.1 Stature

Each participant was requested to remove excess clothing (including shoes, necklaces and jewellery) before taking position on the stadiometer. The stature of players was measured while standing in the anatomical position with their feet together and heels pressed against the base of a Harpenden stadiometer (London, United Kingdom). Stature was measured (to the nearest millimeter) at the highest point of the vertex while the head assumed a neutral position.

3.6.1.2 Body Mass and Body Mass Index (BMI)

Following stature, body mass was measured to the nearest 0.01 kg, on a calibrated LifeMax electronic scale (Johannesburg, South Africa). Mass was measured both with and without protective cricket kit. The body mass index calculation (Equation 4) allowed for the classification of each individual into theoretical weight classifications (underweight, normal weight, overweight, or obese).

Equation 4: Body mass index (BMI).

$$\text{BMI (kg/m}^2) = \frac{\text{BM}}{(\text{Stature})^2}$$

Where: BM = Body Mass (kg)

3.6.1.3 *Body Fat Percentage*

Skinfolds were estimated using Harpenden Skinfold callipers (Sussex, United Kingdom) with the Jackson and Pollock (sum of seven) method (Jackson & Pollock, 1978). The sites recorded included, the chest, triceps, subscapular, suprailliac, abdominal, thigh and axilla. Three measures of each site were obtained and from this body fat percentage was calculated. The technique was as follows; the thumb and index finger of the left hand raised a double layer of skin and underlying adipose tissue. The tips of the callipers were then placed 10 mm below and perpendicular to the pinch, halfway between the crest and the base of the anatomical site. Subsequently, the pinch of the left hand was released allowing measurement of subcutaneous adipose tissue. To increase the reliability of measurement, only the principal researcher performed measurements.

3.6.2 Additional Instrumentation and Equipment

3.6.2.1 *Indoor High-Performance Centres*

Schoolboy batters were tested at the Kingswood College high performance centre in Grahamstown, South Africa. The running surface in this centre is composed of an artificial vulcanized rubber and had four full-length (21 x 5 m) cricket lanes. Similarly, at the Cricket South Africa centre of excellence (Pretoria, South Africa), where the academy batters were tested, the batting surface was composed of high-density artificial turf. This facility also housed four full-length cricket lanes. In spite of the differences in surface type, each of these surfaces promote a high friction-coefficient and reduced the chances of a batter slipping while running. Each centre had its own air conditioning system and temperatures were standardised across experimental sessions. Each centre was brightly lit, however illumination was not controlled.

3.6.2.2 Protective Cricket Kit

Participants were required to bring and wear their own protective cricket kit. This criterion was put in place for hygiene reasons as well as to ensure the protection of the body. This criterion also allowed batters to be comfortable during experimentation in kit that was their own. The protective kit included, leg pads, ball box, thigh pads, gloves, and a helmet. All batters were requested to wear traditional cross training shoes during the protocol. This was standardised between phases.

3.7 Experimental Procedures

3.7.1 Phase 1: Pre-Screening and Familiarisation Session

Prior to the familiarisation session, consent was obtained from each batter's school and parent. Familiarisation took place at each respective school, approximately one week before experimentation. The purpose of this session was to introduce the research to the participants, to record baseline measures and obtain player assent. Once the aims and objectives of the research had been explained, the principal researcher worked with each participant individually and conducted the following demographic (age, ethnicity, cricket history and practice philosophies), anthropometric (stature, mass, body mass index, body fat percentage) and reference measures (heart rate and cognitive performance). To ensure a smooth transition to the experimental session, participants were familiarised to the cognitive test battery, BATEX, all measuring devices and procedures. This included a single trail of the cognitive test battery and a verbal summary of the BATEX simulation. Once this summary was delivered the first over of the simulation was played to the batter so that each player was aware of the batting procedures.

3.7.2 Phase 1: Experimental Session

The duration of the data collection session approximated four hours and allowed sufficient time for warm-up and cool down. Players were fitted with the Polar heart rate belt and immediately conducted the *pre-test* cognitive test battery. Thereafter, nude body mass was taken and the warm-up commenced. Players were then taken through a 15 min cricket-related warm up that included: 10 submaximal shuttles, 20 dynamic lunges, 10 dynamic squats, 25 m high-knee runs, 25 m 'butt-kick' shuttle, 25 m high-kick walk-through, 10 jump squats and 10 torso rotations. Players then performed self-selected stretches.

After this batters dressed in full protective kit whereafter the ‘kitted’ body mass was measured and the protocol initiated. BATEX was conducted as described by (Houghton et al., 2011a) and according to the audio track. The only deviation from BATEX, was for three breaks to facilitate cognitive data collection (i.e. following overs 5, 15 and 25). During each cognitive test battery, heart rate variability was assessed and as far as possible, identical testing procedures were followed. Procedures were also standardised between participants. Following *CTB 3*, batters consumed 250 ml of an isotonic sports drink. Once the BATEX protocol was completed, the *post-test* measures of cognitive performance were conducted. Thereafter, body mass in cricket kit as well as nude body mass was measured. Finally, players were taken through the same set of stretches as conducted before experimentation to cool down.

3.7.3 Phase 2 and 3: Pre-Screening and Familiarisation Session

Approximately 2 weeks before experimentation the academy batters attended a similar familiarisation session to that of *phase 1*. In contrast to *phase 1*, each participant completed two trails of the CogState test battery whereafter batters were tested to gauge their familiarity with each task. Batters were also familiarised with the vertical jump procedures, the board, correct starting position and how to perform each jump with the correct technique. Thereafter, each participant performed numerous trials of each jump to the satisfaction of the principal researcher.

3.7.4 Phase 2 and 3: Experimental sessions

Experimentation started approximately two weeks after the habituation session and was conducted at the Cricket South Africa Centre of Excellence in Pretoria, South Africa. The duration of the *test* and *retest* session was approximately 3 hrs 40 mins including warm-up and cool down. Procedures and warm-up were the same as *phase 1* but included six vertical jump trials (three SJ and three CMJ) that followed the warm-up. The protocol was followed as described by (Houghton et al., 2011a) with only one deviation (post over 15) to facilitate cognitive data collection. With the exception of water, which was consumed *Ad Libitum*, no other substrates were permitted. Once the BATEX protocol was completed, players were weighed with their kit whereafter *post-test* vertical jump measures were completed. Immediately after, the final cognitive performance battery was conducted. The final measurement taken was nude body mass, whereafter, cool down commenced. Importantly, the procedures carried out in *phase 2* were replicated in the in *phase 3*. The timeframe between *test* and *retest* sessions was approximately 10 days for each batter.

3.8 Statistical Hypotheses

The following null hypotheses were generated for investigation:

1. Prolonged batting will have no effect on information processing. This hypothesis applies individually to each of the cognitive domains measured (psychomotor function; visual attention; vigilance; visual learning and memory; attention and working memory and executive functions).

   Ho: $\mu CTB1 = \mu\ CTB2 = \mu\ CTB3 = \mu\ CTB4 = \mu\ CTB5$
   Ha: $\mu CTB1 \neq \mu\ CTB2 \neq \mu\ CTB3 \neq \mu\ CTB4 \neq \mu\ CTB5$

2. Prolonged batting will have no effect on time domain and frequency spectrum parameters. This hypothesis applies individually to each measure of heart rate variability.

   Ho: $\mu HRV\text{-}BE1 = \mu HRV\text{-}BE2 = \mu HRV\text{-}BE3 = \mu HRV\text{-}BE4 = \mu HRV\text{-}BE5$
   Ha: $\mu HRV\text{-}BE1 \neq \mu HRV\text{-}BE2 \neq \mu HRV\text{-}BE3 \neq \mu HRV\text{-}BE4 \neq \mu HRV\text{-}BE5$

3. The differential cognitive demands of each task will have no effect on heart rate variability parameters. This hypothesis applies individually to each measure of heart rate variability.

   4. Ho: $\mu HRV\text{-}TE1 = \mu HRV\text{-}TE2 = \mu HRV\text{-}TE3 = \mu HRV\text{-}TE4 = \mu HRV\text{-}TE5$
   5. Ha: $\mu HRV\text{-}TE1 \neq \mu HRV\text{-}TE2 \neq \mu HRV\text{-}TE3 \neq \mu HRV\text{-}TE4 \neq \mu HRV\text{-}TE5$

6. Prolonged batting will have no effect on sprint times.

   Ho: $\mu ST_{(Stage\ 2)} = \mu ST_{(Stage\ 4)} = \mu ST_{(Stage\ 6)}$
   Ha: $\mu ST_{(Stage\ 2)} \neq \mu ST_{(Stage\ 4)} \neq \mu ST_{(Stage\ 6)}$

7. Prolonged batting will have no effect on batting accuracy.

   Ho: $\mu BP_{(pre)} = \mu BP_{(Over\ 5)} = \mu BP_{(Over\ 15)} = \mu BP_{(Over\ 25)} = \mu BP_{(Over\ 30)}$

$Ha: \mu BP_{(pre)} \neq \mu BP_{(Over\ 5)} \neq \mu BP_{(Over\ 15)} \neq \mu BP_{(Over\ 25)} \neq \mu BP_{(Over\ 30)}$

8. The physiological responses of batters will remain unchanged throughout the simulation. This hypothesis applies individually to both heart rate and body mass.

   $Ho: \mu P_{(Stage\ 1)} = \mu P_{(Stage\ 2)} = \mu P_{(Stage\ 3)} = \mu P_{(Stage\ 4)} = \mu P_{(Stage\ 5)} = \mu P_{(Stage\ 6)}$
   $Ha: \mu P_{(Stage\ 1)} \neq \mu P_{(Stage\ 2)} \neq \mu P_{(Stage\ 3)} \neq \mu P_{(Stage\ 4)} \neq \mu P_{(Stage\ 5)} \neq \mu P_{(Stage\ 6)}$

9. The perceptual responses of batters will remain unchanged throughout the simulation. This hypothesis applies individually to both central and local ratings of perceived exertion.

   $Ho: \mu PER_{(Stage\ 1)} = \mu PER_{(Stage\ 2)} = \mu PER_{(Stage\ 3)} = \mu PER_{(Stage\ 4)} = \mu PER_{(Stage\ 5)} = \mu PER_{(Stage\ 6)}$
   $Ha: \mu PER_{(Stage\ 1)} \neq \mu PER_{(Stage\ 2)} \neq \mu PER_{(Stage\ 3)} \neq \mu PER_{(Stage\ 4)} \neq \mu PER_{(Stage\ 5)} \neq \mu PER_{(Stage\ 6)}$

10. Prolonged batting will have no effect on vertical jump height.

    $Ho: \mu VJ_{(pre)} = \mu VJ_{(post)}$

    $Ha: \mu VJ_{(pre)} \neq \mu VJ_{(post)}$

11. There will be no differences in cognitive performance, batting performance, physiological responses and perceptual response between the test and retest sessions. This hypothesis applies to each dependent variable individually.

    $Ho: \mu T = \mu RT$

    $Ha: \mu T \neq \mu RT$

Where: CTB1-5 = CogState test battery

HRV- BE = Heart rate variability (battery effect)

μHRV- TE = Heart rate variability (task effect)

ST = Sprint times

VJ = Vertical jump height

P = Physiological Responses

PER = Perceptual responses

T = Test session

RT = Retest session

3.9 Data Handling and Analysis

To safeguard data integrity, CogState data were recorded in an encrypted data file which was reduced and analysed using DataPoint analysis software (CogState LTD, Melbourne). Responses to each trial were recorded separately, and speed and accuracy measures from the correct responses were determined for each task. Once uploaded to DataPoint[7], data processing would allow a series of test reports to be produced. Data point applied a series of normalised steps to eliminate non-normally distributed data. Response time was normalised with a logarithmic base 10 transformation and accuracy rates were normalised with an Arcsine transformation of the square root of the proportion of correct responses. Thereafter, the data was transferred to Microsoft Excel where the data was analysed further.

While differing methodologies do not allow for statistical comparisons, to illustrate overall performance and to allow comparison between samples, the inverse efficiency score (ratio between response time and accuracy) was calculated. This measure is computed by dividing mean response times attained per task by the corresponding error percentage (Bruyer & Brysbaert, 2011). In instances with equal response times a higher accuracy rate produces lower inverse efficiency, indicating improved performance.

3.10 Statistical Analysis

All data were processed using StatSoft, Inc. (2015) STATISTICA©, Version 12.0. Shapiro–Wilk's W test confirmed normality of distributions. Following this, descriptive statistics were performed in order to determine the means, standard deviations and coefficient of variation from the respective conditions. To determine the strength of association between variables, Pearson's correlation coefficient was calculated and presented accordingly. A within-group

---

[7] URL: https://secure.cogstate.com/research/rs/login.cfm

one-way ANOVA compared measures between stages (1–6) and assessments (1–5). Tukey's post-hoc analyses compared pairwise means. Significance was set at $p<0.05$. Cohen's d effect sizes (Cumming, 2014: d: 0.2–0.49, small effect; 0.5–0.79, moderate effect; ≥0.8, large effect) were calculated to assess the magnitude of the difference over time.

CHAPTER IV - RESULTS: SCHOOLBOY BATTERS - PHASE 1

The subsequent results chapter will highlight the main findings of schoolboy batters who completed a single experimental session with five cognitive assessments.

4.1 Key Considerations for Statistical Interpretation

Due to the nature of the study, the extent and complexity of the data, only results that demonstrated main effects ($p<0.05$; $d>0.2$) will be discussed. Throughout the results section and discussion chapter, *time/stage, task* and *battery effects* will be referred to.

- A *time effect/effect of time* or *stage effect* will refer to changes in performance that occur during the simulation.

- A *task effect* will refer to changes in performance that coincided between tasks. For example; physical performance would refer to differences in run type (sprint times) and batting accuracy. With regard to cognitive performance, these are between-task differences during each assessment for the *Groton maze-learning* (*Maze*), *detection*, *identification*, *one card-learning* and *one-back* tasks.

- A *battery effect* refers to differences obtained during cognitive assessments and is classified between the five test batteries, *pre-test*, *CTB 2* (post the 5th over), *CTB 3* (post the 15th over), *CTB 4* (post the 25th over) and *post-simulation*.

Unless otherwise stated, all statistical analyses were performed with a 95% confidence interval ($p<0.05$). Furthermore, where appropriate 'Cohen's *d* effect sizes (*d*: 0.2–0.49, small effect; 0.5–0.79, moderate effect; ≥0.8, large effect) were calculated to assess the magnitude of the difference over time (Cumming, 2014). Results are presented as mean ± standard deviation (*SD*) and where appropriate (p = significance level; d = Cohen's d).

4.2 Results Overview

Table X displays the main effects derived from null-hypothesis testing for the schoolboy batters. The physiological demand increased ($p<0.01$) over time and batters lost a significant amount of mass ($p<0.01$) over the 30-over period. Batters perceived more cardiovascular strain ($p<0.01$) than musculoskeletal strain, but both perceptions increased ($p<0.05$) over time. Sprint times slowed ($p<0.01$) over time with the slowest times recorded in the final stage of batting.

Table X: Main effects results overview (**X** – denotes a difference, where $p<0.05$ and **XX** denotes a difference, where $p<0.01$).

		TIME EFFECT	***TASK EFFECT***	***BATTERY EFFECT***
PHYSIOLOGICAL PERFORMANCE	*Heart rate*	**XX**		
	Mass - Fluid balance	**XX**		
	Relative sweat loss			
BATTING PERFORMANCE	*Sprint times*	**XX**	**X**	
	Batting Accuracy			
PERCEPTUAL RESPONSES	*Central RPE*	**X**	**XX**	
	Local RPE	**XX**	**XX**	
COGNITIVE PERFORMANCE	*Heart rate*		**XX**	**XX**
	Heart Rate Variability		**XX**	**XX**
	Maze Task	**X**		
	Detection			
	Identification			
	One Card-learning	**XX**		
	One Back			

Resultantly, cognitive performance deteriorated ($p<0.05$) in *maze* task, but improved in the *one card-learning* task ($p<0.01$). While performing cognitive tasks, heart rate variability decreased between batteries (between batteries; $p<0.01$), however, with increasing time on task heart rate variability increased ($p<0.01$).

4.3 Batting Performance

Physical performance was assessed with sprint times and batting accuracy. These two variables provided a means to monitor muscular performance (sprint times) as well as skill (batting accuracy). Batters completed 105.5 shuttles (17.68 m) during the simulation. The total distance covered running between the wickets amounted to 1865.2 m (859.5 $m.h^{-1}$). When detailed as high- and low-intensity efforts, batters completed 64.5 (1140.4 m) high-intensity and 41 (724.9 m) low-intensity shuttles.

4.3.1 Sprint Times

A *time effect* for mean sprint times (*p*<0.01) showed that players slowed over time, while *task effects* demonstrated that singles (*p*<0.02), triples (*p*<0.03) and fours (*p*<0.01) became progressively slower with time.

Table XI: One way analysis of variance (ANOVA) of mean sprint times and individual run denominations. (SS = sum of squares, DoF = degrees of freedom, MS = mean square, F = 'F' statistic, p = p-value where red values indicate significant differences (*p*<0.05)

Sprint Times		**SS**	**DoF**	**MS**	**F**	**p**
Average	STAGE	0.075	2, 26	0.037	13.194	0.00011
Singles	RUNTYPE	0.031	2, 26	0.016	5.297	0.01176
Doubles	RUNTYPE	0.016	2, 26	0.008	1.248	0.30385
Triples	RUNTYPE	0.033	1, 13	0.033	6.488	0.02432
Fours	RUNTYPE	0.177	2, 26	0.089	8.497	0.00145

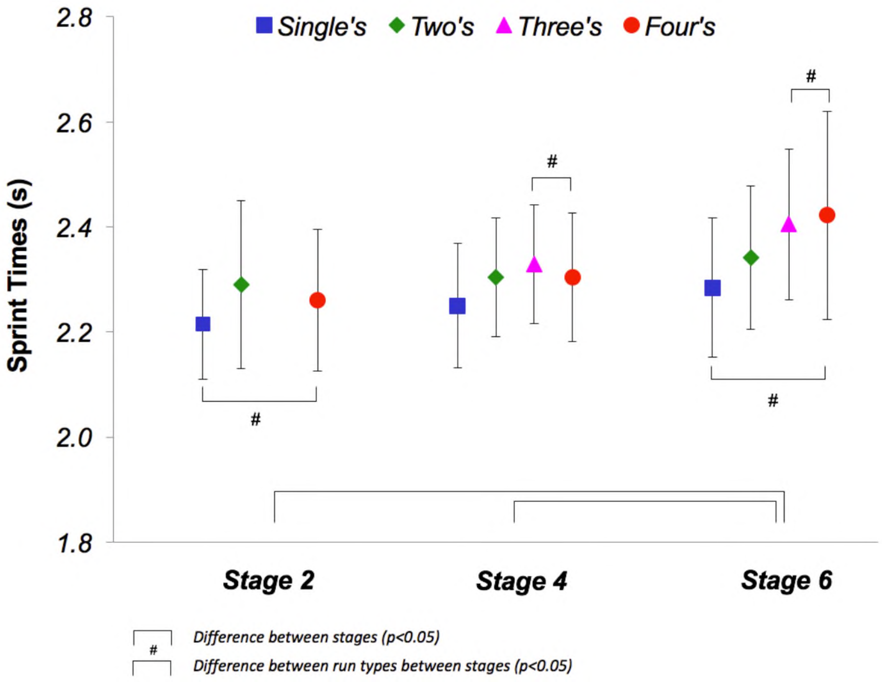


Figure 8: Sprint performance during high-intensity stages for single, double and triple shuttles as well as for boundaries. No double shuttles were performed in stage 2 (all values mean ± SD).

Mean sprint times were slower in stage 6 (2.36 ± 0.14 s) compared to stages 2 (2.25 ± 0.12: *p*<0.01; *d* = 0.84) and 4 (2.29 ± 0.10: *p*<0.02; *d* = 0.54). Additionally, times taken to complete singles (*d* = 0.58) and fours (*d* = 0.96) in stage 6 were slower (*p*<0.01) when compared to that of stage 2 (Figure 8). Likewise, sprint times for threes and fours in stage 6 were slower than those in stage 4 (*p*<0.03; *d* = 0.59 and *p*<0.02; *d* = 0.72, respectively). Sprint results suggest that the simulation adequately fatigued batters. Variability in sprint times was highest in the final stage of testing, suggesting that the protocol fatigued players differentially. The highest variability was observed for triple shuttles in stage 6. Effect sizes support the statistical analyses conducted with moderate and strong effects between stages as well as run types.

4.3.2 Batting Accuracy

Table XII: One way ANOVA for batting accuracy.

Batting Accuracy	SS	DoF	MS	F	p
OVER	2409.7	4, 52	602.423	2.259	0.07525

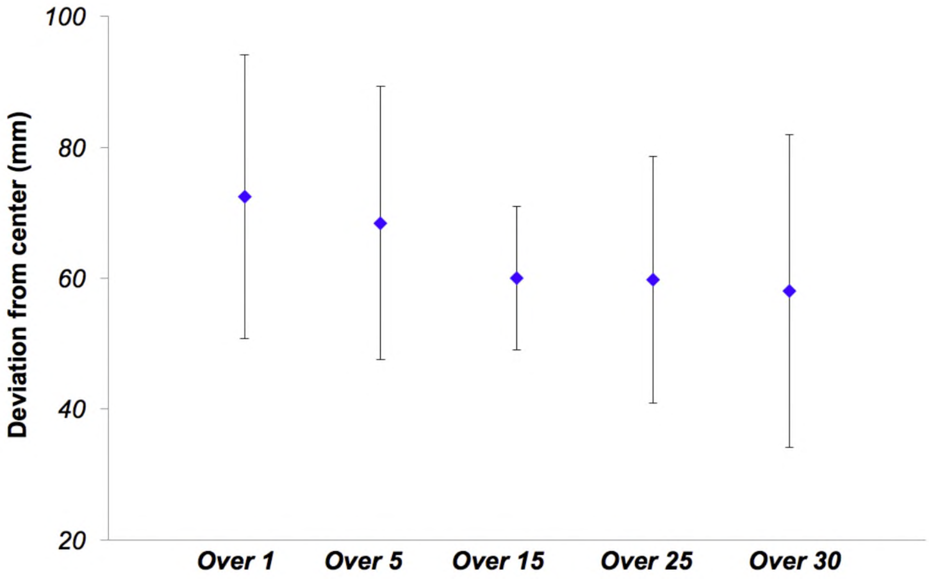


Figure 9: Mean deviation (± SD) in accuracy over time. Lower value indicates closer proximity to the centre of the bat.

Accuracy improved (*p*=0.08; *d* = 0.63) over time and was highest in the final over. (Figure 9). Effect sizes demonstrate moderate and large improvements in accuracy from the onset of batting until completion (Table XIII).

Table XIII: Cohen's *d* comparing batting accuracy between overs.

OVER	*OVER*	*OVER*	*OVER*	*OVER*	*OVER*	*OVER*	*OVER*	*OVER*	*OVER*
1 vs 5	*1 vs 15*	*1 vs 25*	*1 vs 30*	*5 vs 15*	*5 vs 25*	*5 vs 30*	*15 vs 25*	*15 vs 30*	*25 vs 30*
0.19	**0.73**	**0.62**	**0.63**	**0.51**	**0.43**	**0.46**	**0.01**	**0.11**	**0.08**

Cohen's d: 0.2 - 0.5 = small effect, 0.51 - 0.8 = medium effect and > 0.8 = large effect

While not statistically different, large improvements in accuracy were evident in the 15th, 25th and 30th overs (*d* = 0.73, 0.62 and 0.63, respectively), with the biggest improvement occurring between the 1st and 15th over (*d* = 0.73). Between-player variability was lowest in the 15th over, where after, variability increased.

4.4 Physiological Responses

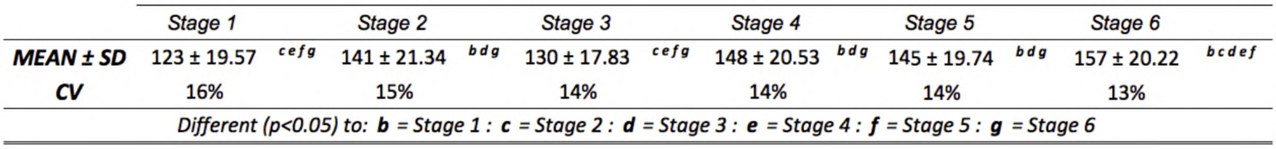
4.4.1 Heart Rate

Table XIV: One way ANOVA of heart rate responses during BATEX.

Heart Rate	SS	DoF	MS	F	p
STAGE	56810	5, 70	11362	44.156	0.00000
OVER	6823	4, 56	1706	16.886	0.00000
STAGE*OVER	15301	20, 280	765	8.918	0.00000

Heart rates were higher (*p*<0.01) during the maximal intensity stages when compared to the self-selected stages (Table XV). An *interaction effect* was observed between stage and over, where, heart rates were higher (*p*<0.01) in overs 3-5 of each stage when compared to overs 1 and 2.

Table XV: Heart rate responses during the BATEX. Stages 1, 3 and 5 = self-selected and stages 2, 4 and 6 = maximal intensity (all values mean ± SD).



	Stage 1		Stage 2		Stage 3		Stage 4		Stage 5		Stage 6	
MEAN ± SD	123 ± 19.57	cefg	141 ± 21.34	bdg	130 ± 17.83	cefg	148 ± 20.53	bdg	145 ± 19.74	bdg	157 ± 20.22	bcdef
CV	16%		15%		14%		14%		14%		13%	

Different (p<0.05) to: ***b*** *= Stage 1 :* ***c*** *= Stage 2 :* ***d*** *= Stage 3 :* ***e*** *= Stage 4 :* ***f*** *= Stage 5 :* ***g*** *= Stage 6*

Heart rate increased steadily over time, and was highest in stage 6 (157 ± 20.22 bt.min^{-1}) compared to stage 4 (148 ± 20.53 bt.min^{-1}: $p<0.02$; $d = 0.52$) and stage 2 (141 ± 21.34 bt.min^{-1}: $p<0.01$; $d = 0.91$) (Figure 10). The between-participant variability for heart rate is comparable between stages; however, variability between overs is lowest in the final stage.

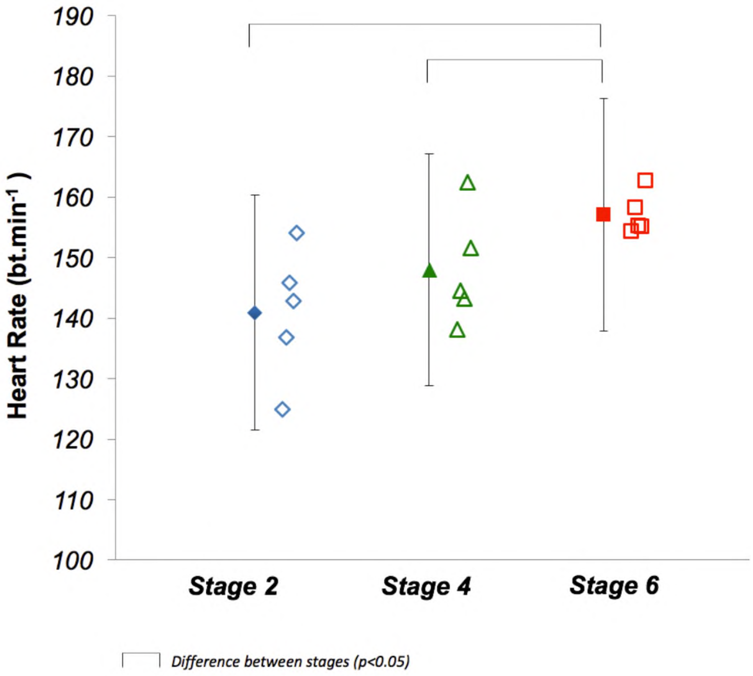


Figure 10: Heart rate responses during maximal intensity stages. Mean stage responses demarcated by the single data point with error bar, and mean over responses demarcated by data points without error bars (all values mean ± SD).

4.4.2 *Fluid balance and Sweat Loss*

A *time effect* for reduced body mass ($p<0.01$; $d = 0.09$) was observed. In addition, an effect of kit was also observed, with body mass being higher ($p<0.01$) when fully ‘kitted’.

Table XVI: One way ANOVA for body mass recordings obtained *pre* and *post-test* both with and without kit.

Body Mass	SS	DoF	MS	F	p
KIT	172.043	1, 14	172.043	1134.882	0.00000
PRE-POST	15.000	1, 14	15.000	52.434	0.00000
KIT*PRE-POST	0.017	1, 14	0.017	0.260	0.61824

On average, body mass decreased by 0.97 kg (1.27%) with 1.01 L of fluid (1.36 %BM) lost through sweat. Absolute and relative sweat rate were 0.25 and 0.34 $L.h^{-1}$, respectively.

4.5 Perceptual Responses

A *time* and *interaction effect* for both central ($p<0.05$) and local ($p<0.01$) perceptions of exertion was demonstrated. Comparisons between central and local RPE also demonstrated *time* and *interaction effects* ($p<0.01$).

Table XVII: One way ANOVA results for central and local ratings of perceived exertion (RPE) as well as multivariate ANOVA results comparing central and local RPE.

Ratings of Perceived Exertion		SS	DoF	MS	F	p
Central RPE	STAGE	2112.18	5, 70	422.436	79.472	0.00000
	OVER	167.36	4, 56	41.841	56.187	0.00000
	STAGE*OVER	65.36	20, 280	3.268	5.851	0.00000
Local RPE	CEN-LOC	1566.14	5, 70	313.229	62.168	0.00000
	STAGE	80.41	4, 56	20.103	61.676	0.00000
	CEN-LOC*STAGE	16.60	20, 280	0.830	1.925	0.01104
Central vs. Local RPE	STAGE	0.64	1, 14	0.642	4.872	0.04448
	OVER	253.98	2, 28	126.992	80.357	0.00000
	STAGE*OVER	22.33	2, 28	11.166	33.437	0.00000

In the maximal intensity stages, and when compared to local RPE, central RPE was rated higher in stages 4 ($p<0.01$) and 6 ($p<0.01$) of the simulation (Table XVIII and Figure 11).

Batters rated local RPE highest in stage 6 rated and between stage differences were as follows: stage 6 vs. 2 (*p*<0.01; *d* = 2.37) and stage 6 vs.4 (*p*<0.01; *d* = 1.29).

Table XVIII: Central and local ratings of perceived exertion recorded during the BATEX simulation (all values mean ± SD with CV representing coefficient of variation).

	CENTRAL					
	Stage 1	*Stage 2*	*Stage 3*	*Stage 4*	*Stage 5*	*Stage 6*
MEAN ± SD	8.41 ± 1.69 ^{cdefg}	10.09 ± 2.13 ^{befg}	10.36 ± 2.07 ^{befg}	12.56 ± 1.85 ^{bcdg}	13.29 ± 1.93 ^{bcdg}	14.83 ± 1.66 ^{bcdef}
CV	20%	21%	20%	15%	15%	11%
	LOCAL					
	Stage 1	*Stage 2*	*Stage 3*	*Stage 4*	*Stage 5*	*Stage 6*
MEAN ± SD	7.91 1.39 ^{cdefg}	9.11 ± 1.78 ^{befg}	9.69 ± 1.76 ^{befg}	11.11 ± 1.96 ^{bcdg}	11.97 ± 1.94 ^{bcdg}	13.51 ± 2.08 ^{bcdef}
CV	18%	19%	18%	18%	16%	15%

Different (p<0.05) to: ***b*** *= Stage 1 :* ***c*** *= Stage 2 :* ***d*** *= Stage 3 :* ***e*** *= Stage 4 :* ***f*** *= Stage 5 :* ***g*** *= Stage 6*

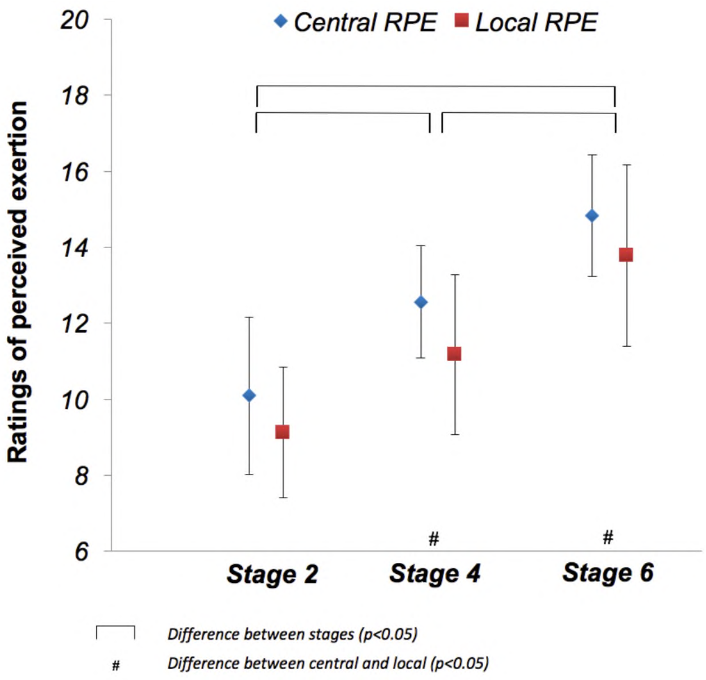


Figure 11: Ratings of perceived exertion for central and local RPE (all values mean ± SD).

Central RPE also increased between stage 2 and 4 (*p*<0.01; *d* = 1.49) and between stages 2 and 6 (*p*<0.01; *d* = 2.49): in both comparisons, stage 6 was rated higher. Differences were also observed between stage 4 and 6 (*p*<0.01; *d* = 1.39). The highest ratings of perceived exertion (stage 6: 14.82 ± 1.59) coincided with the highest heart rate responses (157 ± 20.72 bt.min^{-1}), indicating that participants were accurate in their ratings. While between-participant variability was similar for central and local RPE, central variability was higher and follows an inverted U-shaped curve. Conversely, variability in local RPE continually increases over time.

4.6 Cognitive Performance

4.6.1 Introduction

A primary outcome variable is the variable by which performance in each cognitive domain is assessed, specifically these are; response time (log^{10}- transformed correct response times) and response accuracy (number of correct responses divided by the total number of responses). In the *detection* and *identification* tasks, response time is the primary outcome variable. For the *one-back* and *one card-learning* tasks, accuracy is the primary outcome variable. In each, higher response time or lower accuracy indicates reduced performance. Within the *maze* task, error rate is the primary outcome measure. Additionally, heart rate variability was assessed to determine the level of engagement (cognitive workload) within each task, and battery, these results are also reported in this section.

4.6.2 Time-On-task

The time stamp of the start and end of each task was monitored and recorded so that the time spent conducting each task and battery could be compared.

Table XIX: Statistical interactions for time-on-task.

Time-on-Task		**SS**	**DoF**	**MS**	**F**	**p**
Maze	BATTERY	25086	4, 52	6271.443	7.392	0.00009
Detection	BATTERY	1357	4, 52	339.286	1.095	0.36885
Identification	BATTERY	159	4, 52	39.821	0.326	0.85923
One card-learning	BATTERY	834	4, 53	208.571	0.501	0.73487
One-back	BATTERY	544	4, 52	136.071	0.817	0.52048
Total Duration	BATTERY	36748	4, 52	9186.964	4.600	0.00296

Total time conducting the cognitive test battery duration decreased (p<0.01) over time. *Pre-test* task time 00:16:11 ± 00:01:20 (hh:mm:ss) was longer compared to *CTB 4* (00:15:02 ± 00:00:53) and *post-test* (00:15:00 ± 00:01:00). Additionally, the time required to complete the maze task also decreased significantly (p<0.01) between batteries. In this regard, the third, fourth and final assessments required significantly less time to complete the *maze* than the *pre-test* battery. No other effects were observed.

4.6.3 Primary Outcome variables

No *time effects* were observed for speed of processing. *Time effects* were however observed for accuracy rates in the *detection* and *one card-learning* tasks ($p<0.01$). The *detection*, *identification* and *one-back* tasks demonstrate a non-significant ($p>0.05$) decrement in processing speed between batteries (Table XX).

Table XX: One way ANOVA results for speed and accuracy responses in the *detection*, *identification*, *one-back* and *one card-learning* tasks.

Speed of Processing		**SS**	**DoF**	**MS**	**F**	**p**
Detection	BATTERY	0.005	5, 70	0.001	0.678	0.64145
Identification	BATTERY	0.015	5, 70	0.003	1.494	0.20301
One card-learning	BATTERY	0.016	5, 70	0.003	1.444	0.21939
One-back	BATTERY	0.018	5, 70	0.004	1.370	0.24607

Accuracy		**SS**	**DoF**	**MS**	**F**	**p**
Detection	BATTERY	0.286	5, 70	0.057	6.215	0.00008
Identification	BATTERY	0.042	5, 70	0.008	0.466	0.80021
One card-learning	BATTERY	0.087	5, 70	0.017	3.386	0.00849
One-back	BATTERY	0.102	5, 70	0.020	1.621	0.16576

Table XXI: Performance responses obtained during the *detection*, *identification*, *one-back*, *one card-learning* and *maze* tasks[8] (response time = log^{10}ms, accuracy = arcsine proportion correct, all values mean ± SD).

	Pre-Test		***CTB 2***		***CTB 3***		***CTB 4***		***Post-Test***	
	Mean	***SD***	***Mean***	***SD***	***Mean***	***SD***	***Mean***	***SD***	***Mean***	***SD***
Detection										
Response Time	2.47	0.05	2.49	0.06	2.49	0.05	2.49	0.07	2.49	0.06
Accuracy	1.49	0.13 ^{a}	1.52	0.10 ^{a}	1.40	0.10 ^{c}	1.45	0.12	1.50	0.11 ^{a}
Identification										
Response Time	2.66	0.05	2.67	0.05	2.67	0.07	2.68	0.08	2.70	0.08
Accuracy	1.39	0.12	1.42	0.12	1.38	0.16	1.39	0.13	1.40	0.12
One-back										
Response Time	2.79	0.07	2.79	0.07	2.79	0.08	2.82	0.09	2.81	0.09
Accuracy	1.37	0.17	1.29	0.14	1.29	0.15	1.29	0.12	1.27	0.19
One card-learning										
Response Time	2.94	0.09	2.94	0.08	2.94	0.06	2.93	0.09	2.90	0.07
Accuracy	0.97	0.10	1.01	0.12 ^{a}	1.00	0.12 ^{a}	0.98	0.14	0.96	0.11
Maze Task										
Speed (mvs.s^{-1})	0.89	0.16	1.01	0.17 ^{a}	1.04	0.17 ^{a}	1.09	0.18 $^{a\,b}$	1.11	0.19 $^{a\,b}$
Errors	41.60	11.99	39.53	11.56 ^{a}	45.53	14.20	42.33	12.32	49.13	12.87 ^{c}

Different to ($p<0.05$): a = baseline : b = pre-test : c = assessment 2 : d = assessment 3 : e = assessment 4.

---

[8] The table has been structured so that tasks within increasing demands are displayed toward the bottom. *detection* = least demand (i.e. simple task) and *maze* = highest demand (i.e. complex task)

Participant accuracy improved over time in the *detection* and *identification* tasks, however, after 15 overs, accuracy was worst in these tasks. When comparing *CTB 2* to *CTB 3*, *detection* accuracy decreased (*p*<0.01; *d* = 1.22) with *CTB 3* showing lowest accuracy rates. A large improvement in *detection* accuracy was, however, observed between *CTB 3* and *post-test*. Response accuracy in the *one-back* task demonstrated a non-significant decline (*p*>0.05) over time, however, the decline was moderate according to Cohens *d* (*pre:* vs. *CTB 2* = 0.54; vs. *CTB 3* = 0.52; vs. *CTB 4* = 0.60; vs. *CTB 5* = 0.61).

Response time during the *one card-learning* task improved over time (*p*=0.33), with small effects observed between all *post-test* comparisons (*post*: vs *pre* = 0.42; vs. *CTB 2* = 0.46; vs. *CTB 4* = 0.32). Also, a moderate effect was observed between *CTB 3* and *post-test* (*d* = 0.50). Response accuracy followed an inverted U-shape, with optimal performance recorded during *CTB 2*. Compared to *pre-test* measures, accuracy during *CTB 2* and *CTB 3* was improved (*d* = 0.43 and 0.33, respectively). Following *CTB 3,* accuracy declined below *pre-test* levels (Figure 12).

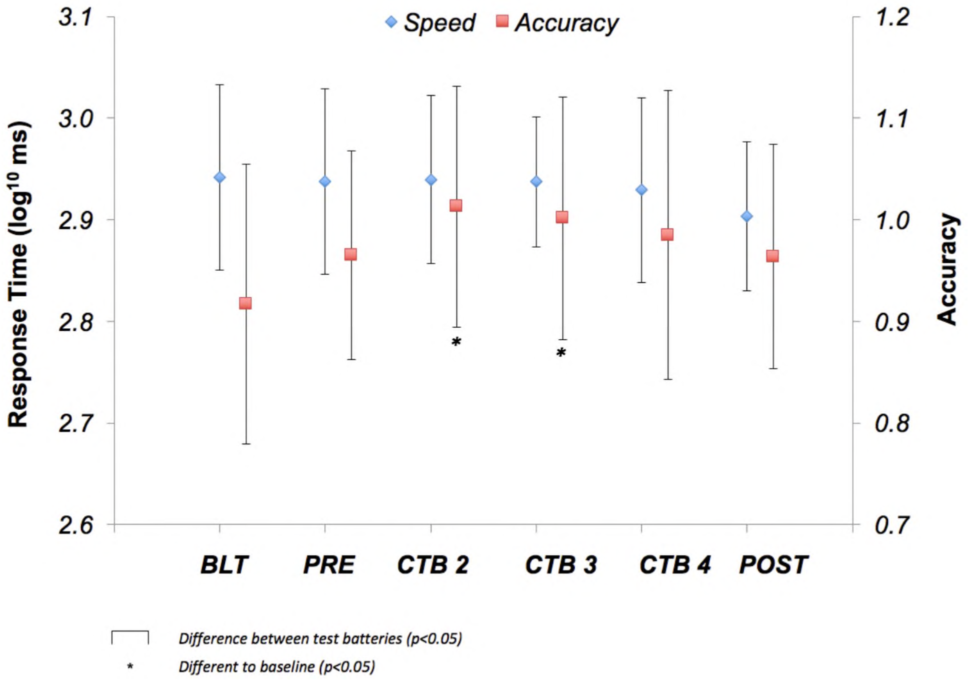
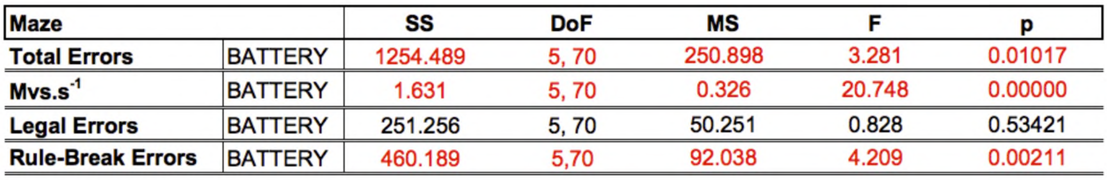


Figure 12: Performance during the *one card-learning* task (response time = log^{10}ms, accuracy = arcsine proportion correct, all values mean ± SD).

When compared to baseline assessments, accuracy was improved in *CTB 2* (*p*<0.01; *d* = 0.75) and *CTB 3* (*p*<0.01; *d* = 0.66). These results indicate that performance is optimal after 15 overs of batting, after which, performance declines.

Results from the *maze* task demonstrated *time effects* for total errors and speed of processing (Table XXII). When compared to *pre-test* responses (0.89 ± 0.16 moves/sec), speed of processing was faster (*p*<0.01) during *CTB 3* (1.04 ± 0.17; *d* = 0.91), *CTB 4* (1.09 ± 0.18; *d* = 1.20) and *post-test* (1.11 ± 0.19; *d* = 1.32). Additionally, a moderate effect between *pre-test CTB 2* was observed (*d* = 0.73). Response time at baseline was slower than all other assessments (Figure 13).

Table XXII: One way ANOVA results for the *Groton maze-learning task*.



Maze		SS	DoF	MS	F	p
Total Errors	BATTERY	1254.489	5, 70	250.898	3.281	0.01017
Mvs.s^{-1}	BATTERY	1.631	5, 70	0.326	20.748	0.00000
Legal Errors	BATTERY	251.256	5, 70	50.251	0.828	0.53421
Rule-Break Errors	BATTERY	460.189	5,70	92.038	4.209	0.00211

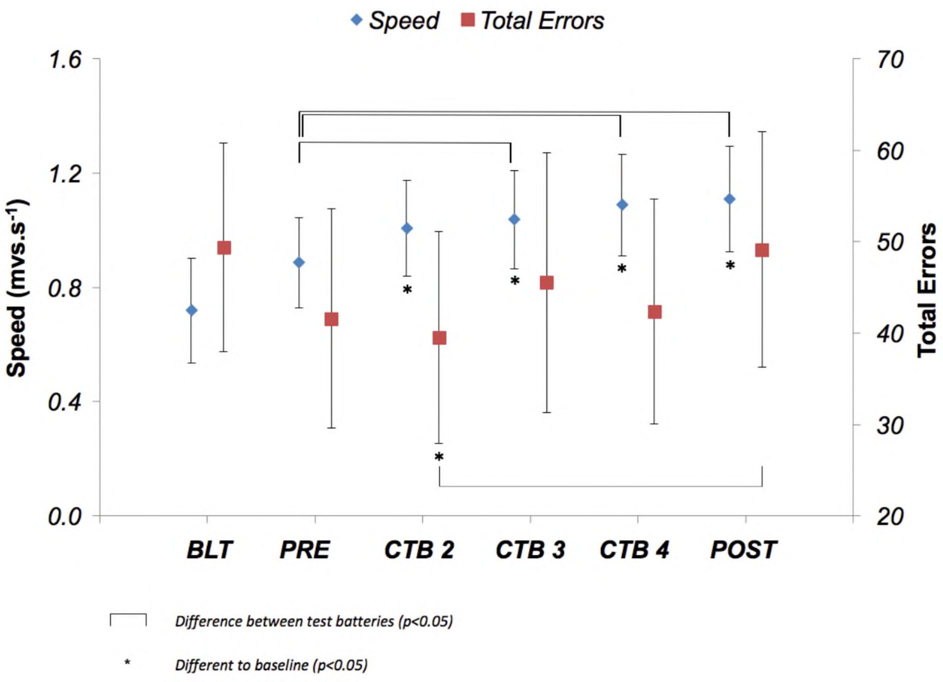


Figure 13: *Groton maze-learning task* performance. Primary outcome measure = total errors (all values mean ± SD).

While participants became faster in the task, the number of errors made increased ($p<0.02$). Error rates increased between *CTB 2* (39.5 ± 11.6) and *post-test* (49.1 ± 12.9) ($p<0.05$; d = 0.80). A moderate increase was also observed between *pre* and *post-test* error rates (p=0.19; d = 0.62). Compared to baseline, the number of errors made during *CTB 2* was significantly reduced ($p<0.04$; d = 0.85). The number of rule break errors (decision making errors) decreased between *pre* (11.1 ± 9.69) and *post-test* (9.13 ± 5.37) (p=0.10; d = 1.29).

4.6.4 Heart Rate Variability

Battery-related differences (changes in responses between cognitive test batteries) will be presented first, followed by task-related differences (differences in responses between individual tasks).

4.6.4.1 Battery-Related Changes in Heart Rate Variability

Battery effects ($p<0.01$) were found in all time domain measures; SDNN, RMSSD, PNN30 and PNN50. Similarly, the following frequency spectrum variables displayed *battery effects*; high-frequency power, low-frequency power, very low-frequency power and the LF:HF ratio (Table XXIII).

Table XXIII: One way ANOVA results for time domain and frequency spectrum components of heart rate variability.

Time Domain		SS	DoF	MS	F	p
HR	BATTERY	7701	4, 44	1925.2	35.475	0.00000
SDNN	BATTERY	8002	4, 44	2000.40	26.055	0.00000
rMSSD	BATTERY	11833	4, 44	2958.4	21.212	0.00000
PNN30	BATTERY	17236	4, 44	4308.97	41.205	0.00000
PNN50	BATTERY	9573	4, 44	2393.16	25.287	0.00000

Frequency Spectrum		SS	DoF	MS	F	p
HF POWER	BATTERY	6468521	4, 44	1617130	2.845	0.03499
LF POWER	BATTERY	16864164	4, 44	4216041	7.951	0.00008
VLF POWER	BATTERY	16258557	4, 44	4064639	5.036	0.00221
LF:HF	BATTERY	2114	4, 44	529	12.756	0.00000
HF (n.u)	BATTERY	0.147	4, 44	0.037	2.181	0.08676
LF (n.u)	BATTERY	0.147	4, 44	0.037	2.181	0.08676

Heart rate increased ($p<0.05$) between test batteries and was highest in the *post-test* assessment ($p<0.01$; d = 3.76) when compared to *pre-test* - Table XXIV). *Post-test* heart rate was also higher ($p<0.01$; d = 1.84) than *CTB 2*. While no other statistical differences were demonstrated in heart rate large effects (>0.8) showing increasing heart rate with time were observed for all *pre-test* comparisons (*pre*: vs*. CTB 2* vs*. CTB 3* vs*. CTB 4* vs*. post-test* - Table XXV).

Time domain measures were highest at *pre-test* and decreased ($p<0.01$) between test batteries, where the lowest responses were recorded *post-test*. Specifically, *pre* vs*. post-test* comparisons demonstrate the following decreases; SDNN ($p<0.01$; d = 2.61); RMSSD ($p<0.01$; d = 2.60), PNN30 ($p<0.01$; d = 3.21) and PNN50 ($p<0.01$; d = 2.55).

Table XXIV: Battery-related changes in time domain parameters of heart rate variability (all values mean ± SD).

	Pre-Test			**CTB2**			**CTB 3**			**CTB 4**			**Post-Test**		
	Mean	**SD**		**Mean**	**SD**		**Mean**	**SD**		**Mean**	**SD**		**Mean**	**SD**	
HR (bt.min^{-1})	68	7.28	b c d e	83	9.42	a c d e	96	14.60	a b	97	12.0	a b	101	10.3	a b
SDNN (ms)	58.4	18.5	b c d e	37.8	13.7	a d e	34.0	14.0	a d	28.3	13.9	a b	20.4	9.1	a b c
rMSSD (ms)	74.1	23.0	b c d e	48.0	16.9	a d	45.4	19.0	a d	38.1	17.8	a	26.9	11.6	a b c
PNN30 (%)	57.0	20.1	b c d e	33.5	19.2	a c d e	21.5	16.6	a b	15.0	14.6	a b	7.37	8.57	a b c
PNN50 (%)	40.5	20.8	b c d e	17.6	14.5	a d e	11.2	11.1	a	7.33	8.81	a b	2.59	3.15	a b

Different ($p<0.05$) to : ***a*** *= pre-test :* ***b*** *= CTB 2 :* ***c*** *= CTB 3 :* ***d*** *= CTB 4 :* ***e*** *= post-test*

Additionally, large effects (>0.8) were demonstrated in all time domain parameters and for all *pre-test* comparisons. Effects sizes for all other comparisons are displayed in Table XXV. Collectively, these results indicate a substantial reduction in heart rate variability due to batting activity.

Table XXV: Time domain effect size comparisons (0.2-0.49 = small; 0.5-0.79 = moderate; >0.8 = large).

	Pre vs. CTB 2	***Pre vs. CTB 3***	***Pre vs. CTB 4***	***Pre vs. Post***	***CTB 2 vs. CTB 3***	***CTB 2 vs. CTB 4***	***CTB 2 vs. Post***	***CTB 3 vs. CTB 4***	***CTB 3 vs. Post***	***CTB 4 vs. Post***
HR	**1.82**	**2.41**	**2.91**	**3.76**	**1.02**	**1.26**	**1.84**	0.08	**0.45**	**0.41**
SDNN	**1.27**	**1.49**	**1.84**	**2.61**	**0.28**	**0.69**	**1.50**	**0.41**	**1.15**	**0.67**
rMSSD	**1.30**	**1.36**	**1.75**	**2.60**	0.14	**0.57**	**1.46**	**0.39**	**1.17**	**0.75**
PNN30	**1.20**	**1.92**	**2.39**	**3.21**	**0.67**	**1.09**	**1.76**	**0.42**	**1.07**	**0.64**
PNN50	**1.28**	**1.76**	**2.08**	**2.55**	**0.50**	**0.85**	**1.43**	**0.39**	**1.06**	**0.72**

Frequency spectrum responses were mixed (Table XXVI). Low-frequency ($p<0.01$; $d = 1.88$) and very low-frequency power ($p<0.01$; $d = 2.17$) spectrums decreased between batteries, with the lowest responses demonstrated *post-test*. When compared to *pre-test*, large effects sizes show decreased low-frequency power between in *CTB 2* (d =1.05), *CTB 4* (d = 1.21) and *post-test* (d = 1.88). Likewise, the very low-frequency power spectrum results for the same comparisons were; d = 1.09, 1.48 and 2.17, respectively. Moderate effects were observed for both low-frequency and very low-frequency power between *CTB 4* and *5* (d = 0.83 and 0.79). Notably, the variability in frequency spectrum values is high across all measures.

Table XXVI: Battery-related changes in frequency spectrum components of heart rate variability (all values mean ± SD).

	Pre-Test			CTB2			CTB 3			CTB 4			Post-Test		
	Mean	**SD**		**Mean**	**SD**		**Mean**	**SD**		**Mean**	**SD**		**Mean**	**SD**	
HF Power (ms^2)	1431	1119	d	513	384		479	487		330	351	a	473	1296	
LF Power (ms^2)	2445	1334	b d e	1305	747	a	1519	1106		1116	806	a	564	476	a
VLF Power (ms^2)	2385	1139	d e	1330	754		1533	1633		988	699	a	550	359	a
LF:HF	2.50	1.68	d e	3.09	1.37	e	3.96	1.39		4.44	1.89	a	6.21	2.81	a b
% LF (LF/HF)	66.2	12.3	c d e	73.2	8.17	e	78.4	5.79	a	79.3	7.60	a	84.1	5.46	a b

*Different (p<0.05) to : **a** = pre-test : **b** = CTB 2 : **c** = CTB 3 : **d** = CTB 4 : **e** = post-test*

The high-frequency power spectrum decreased in a similar fashion, however, the lowest responses were observed during *CTB 4*. Despite no statistical change in high-frequency power between *pre* and *post-test*, a moderate decrease was observed (p=0.17; d = 0.79). Large decreases were also observed in *pre-test* comparisons against, *CTB 2*, *3* and *4* (Table XXVI). In addition to the *battery effects* demonstrated, increases in the LF:HF ($p<0.01$; d = 1.60) ratio and the %LF ($p<0.01$; d = 1.89) were also observed. These parameters were the only frequency spectrum variables to display statistical differences between *CTB 2* and *post-test* ($p<0.01$; d = 1.41 and $p<0.01$; d = 1.58).

Table XXVII: Frequency spectrum effect size comparisons. (0.2-0.49 = small; 0.5-0.79 = moderate; >0.8 = large).

	Pre vs. CTB 2	***Pre vs. CTB 3***	***Pre vs. CTB 4***	***Pre vs. Post***	***CTB 2 vs. CTB 3***	***CTB 2 vs. CTB 4***	***CTB 2 vs. Post***	***CTB 3 vs. CTB 4***	***CTB 3 vs. Post***	***CTB 4 vs. Post***
HF Power	**1.10**	**1.10**	**1.33**	**0.79**	0.08	**0.50**	0.04	**0.35**	0.01	0.15
LF Power	**1.05**	**0.76**	**1.21**	**1.88**	**0.23**	**0.24**	**1.18**	**0.42**	**1.12**	**0.83**
VLF Power	**1.09**	**0.61**	**1.48**	**2.17**	0.16	**0.47**	**1.32**	**0.43**	**0.83**	**0.79**
LF:HF	**0.39**	**0.95**	**1.09**	**1.60**	**0.64**	**0.82**	**1.41**	**0.29**	**1.01**	**0.74**
LF % (n.u.)	**0.67**	**1.27**	**1.28**	**1.89**	**0.74**	**0.77**	**1.58**	0.13	**1.03**	**0.75**
HF % (n.u.)	**0.67**	**1.27**	**1.28**	**1.89**	**0.74**	**0.77**	**1.58**	0.13	**1.03**	**0.75**

Additionally, large increases were observed for *pre-test* comparisons against *CTB 3*; *d* = 0.95, *CTB 4*; *d* = 1.09 and *post-test* *d* =1.60 (Table XXVII). Similarly, a moderate increase was observed between *CTB 4* and *post-test* (*d* = 0.74). In addition, moderate and large effects were observed for the normalised frequency data and ratio data between *pre* and *post-test*.

To summarise, battery-related changes indicate an increase in heart rate with a corresponding decrease in all heart rate variability responses, as the protocol progressed.

4.6.4.2 Task-Related Changes in Heart Rate Variability

This section presents changes in heart rate variability between tasks within a particular battery. *Time-on-task effects* were observed for heart rate and all time domain parameters (Table XXVIII). To isolate these task-related differences, Table XXIX should be read vertically.

Table XXVIII: Statistical interactions for task-related time domain parameters.

Time Domain		**SS**	**DoF**	**MS**	**F**	**p**
HEART RATE	TASK	1886	4, 36	471	34.604	0.00000
	BATTERY	29938	4, 36	7484	72.366	0.00000
	TASK*BATTERY	534	16, 144	33	6.361	0.00000
SDNN	TASK	39517	4, 36	9879	17.963	0.00000
	BATTERY	4361	4, 36	1090	18.391	0.00000
	TASK*BATTERY	811	16, 144	51	1.168	0.30094
RMSSD	TASK	24477	4, 36	6119	17.580	0.00000
	BATTERY	2613	4, 36	653	17.522	0.00000
	TASK*BATTERY	546	16, 144	34	1.208	0.26847
PNN30	TASK	39311	4, 20	9828	38.353	0.00000
	BATTERY	2246	4, 20	562	12.090	0.00004
	TASK*BATTERY	1651	16, 64	103	3.859	0.00003
PNN50	TASK	23087	4, 16	5772	29.043	0.00000
	BATTERY	1466	4, 16	367	9.763	0.00034
	TASK*BATTERY	474	16, 64	30	1.129	0.34918

As *time-on-task* increased, heart rate decreased. No differences were observed during *pre-test* (p>0.05); however, in *CTB 2, 3, 4* and *post-test*, heart rate was highest (p<0.05) in the *maze* task (first task of the battery) when compared with any other task. In the latter test batteries, differences (p<0.05) were also observed between the *detection* and *one card-learning* and as well as between the *detection* and *one-back* tasks (*CTB 4* and *post-test*).

Table XXIX: Time domain changes between tasks. All tasks presented in order of completion (all values mean ± *s*).

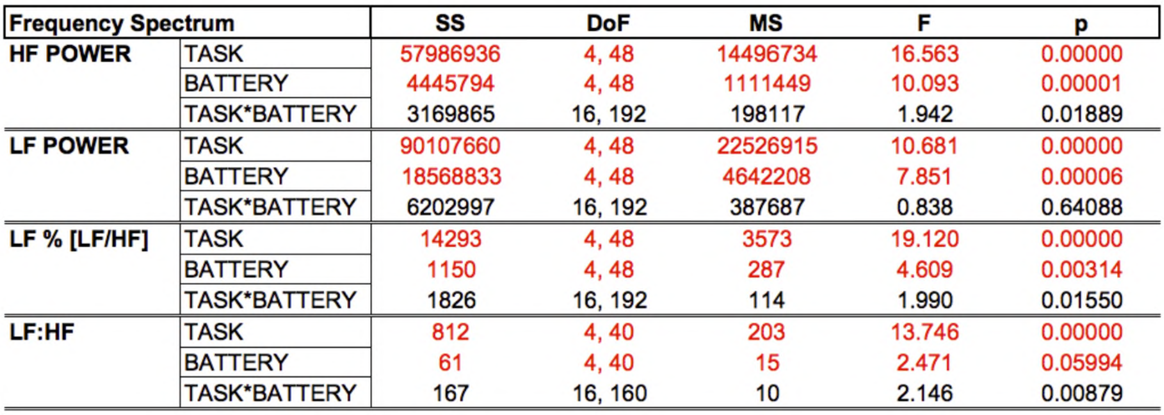
TIME DOMAIN	PRE			CTB2			CTB 3			CTB 4			DUR		
	Mean	SD		Mean	SD		Mean	SD		Mean	SD		Mean	SD	
GMLT															
HR	69	8.30		87	9.31	$^{b\,c\,d\,e}$	95	12.1	$^{c\,d\,e}$	104	12.9	$^{b\,c\,d\,e}$	108	9.91	$^{b\,c\,d\,e}$
SDNN (ms)	38.7	17.1	$^{b\,c\,e}$	22.7	9.38	^{e}	19.2	9.87		15.8	9.29		8.20	4.28	^{e}
rMSSD (ms)	48.8	21.3	$^{b\,c\,e}$	28.3	11.7	^{e}	24.5	12.5		19.9	11.6		10.3	5.39	^{e}
PNN30 %	50.7	19.7		26.7	17.7	^{e}	16.4	15.2	$^{c\,d}$	8.07	9.53	$^{c\,d\,e}$	3.26	3.87	^{e}
PNN50 %	36.6	19.0		12.9	13.3	^{e}	8.62	9.61	^{e}	4.15	4.46		1.66	1.03	
DET															
HR	66	8.38		83	9.58	$^{a\,e}$	92	9.81	^{e}	98	11.9	$^{a\,e}$	103	9.55	$^{a\,d\,e}$
SDNN (ms)	47.3	21.7	^{a}	26.5	10.7		24.5	13.6		20.5	10.9		12.8	7.01	
rMSSD (ms)	59.6	27.2	^{a}	33.7	13.3		31.0	17.2		26.2	14.3		15.8	8.66	^{e}
PNN30 %	53.0	21.4		33.8	15.8		21.6	18.4		16.6	14.3		6.44	7.04	$^{d\,e}$
PNN50 %	39.1	20.9		16.5	11.3		11.3	12.5		7.92	6.78		2.27	1.89	
IDENT															
HR	68	7.73		82	9.80	^{a}	90	10.3	^{a}	95	12.1	^{a}	100	9.97	^{a}
SDNN (ms)	47.4	19.5	^{a}	25.8	10.0		22.6	10.2		19.6	11.9		15.1	7.75	
rMSSD (ms)	59.7	24.2	^{a}	32.7	12.4		28.8	13.5		24.7	15.0		18.8	9.61	
PNN30 %	55.4	17.1		34.4	15.2		22.9	17.8	^{a}	20.6	16.9	^{a}	8.83	8.59	
PNN50 %	38.8	18.8		17.4	13.3		11.9	10.8		10.1	9.46		3.07	3.12	
OCL															
HR	69	6.97		81	10.1	^{a}	90	8.99	^{a}	94	11.9	^{a}	99	11.5	$^{a\,b}$
SDNN (ms)	46.9	19.2		30.2	12.5		24.2	13.0		21.7	12.5		15.4	7.37	
rMSSD (ms)	59.1	24.3		37.9	15.7		30.3	16.3		27.3	16.1		19.3	9.32	
PNN30 %	54.3	19.0		33.7	19.4		20.7	18.3	^{a}	16.8	16.7	^{a}	8.89	10.0	^{b}
PNN50 %	39.7	19.6		19.7	14.7		10.7	12.7		8.48	11.0		3.84	3.75	
OBT															
HR	68	8.69		80	12.2	$^{a\,b}$	92	21.0	$^{a\,b}$	93	11.2	$^{a\,b}$	96	11.5	$^{a\,b}$
SDNN (ms)	48.2	21.0	^{a}	31.4	14.0	^{a}	29.8	14.5		23.7	12.2		20.7	9.10	^{a}
rMSSD (ms)	61.5	27.2	^{a}	39.9	17.4	^{a}	37.7	17.9		30.1	15.6		26.5	12.3	$^{a\,b}$
PNN30 %	55.7	18.8		37.5	20.1	^{a}	29.7	20.6		18.2	15.7	^{a}	12.5	11.7	$^{a\,b}$
PNN50 %	41.4	19.3		23.9	16.7	^{a}	17.9	16.1	^{a}	9.67	11.2		6.27	6.27	

*Different (p<0.05) to : **a** = GMLT : **b** = DETEC : **c** = IDENT : **d** = OCL : **e** = OBT*

SDNN and RMSSD results were the same for all comparisons. Consistent throughout batteries, the *maze* task elicited the lowest heart rate variability, followed by the *identification*, *detection* and *one-back* tasks. During *pre-test*, SDNN and RMSSD were significantly lower (p<0.05) in the *maze* task when compared with the *detection*, *identification* and *one-back* tasks. After the onset of exercise, the number of task-related differences was reduced. *CTB 2* and *post-test* assessments were the only other batteries to demonstrate task-related differences (p<0.05) for SDNN and RMSSD - where variability was lower in the *maze* task compared with the *one-back* task.

The percentage of beats that varied by more than 50 ms (PNN50) increased in *CTB 2* and *CTB 3* between the *maze* and *one-back* tasks (p<0.01, respectively). Additionally, the variability in PNN30 during *CTB 3* and *4* was substantially lower during the *maze* task compared to the *identification* (*p*<0.03 and *p*<0.01, respectively) and *one card-learning* tasks (*p*<0.01 and *p*<0.01, respectively), and in *CTB 4* between the *maze* and *one-back* tasks (*p*<0.01). Also, during *CTB 5* PNN30 was lower in the *detection* task compared to both the *one card-learning* (*p*<0.02) and *one-back* tasks (*p*<0.01). Collectively, the PNN results show that the total variability in heart rate increases with increased time-on-task.

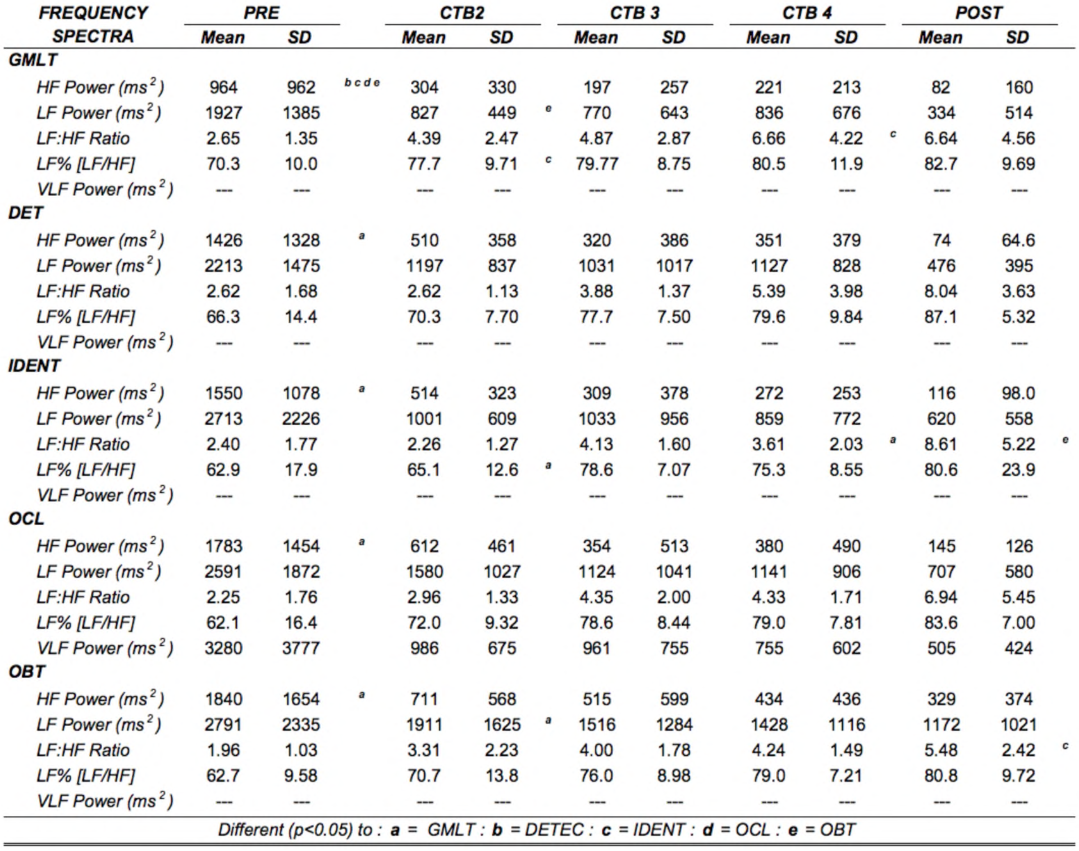
Table XXX: Frequency spectrum statistical effects for task-related comparisons.



Frequency Spectrum		**SS**	**DoF**	**MS**	**F**	**p**
HF POWER	TASK	57986936	4, 48	14496734	16.563	0.00000
	BATTERY	4445794	4, 48	1111449	10.093	0.00001
	TASK*BATTERY	3169865	16, 192	198117	1.942	0.01889
LF POWER	TASK	90107660	4, 48	22526915	10.681	0.00000
	BATTERY	18568833	4, 48	4642208	7.851	0.00006
	TASK*BATTERY	6202997	16, 192	387687	0.838	0.64088
LF % [LF/HF]	TASK	14293	4, 48	3573	19.120	0.00000
	BATTERY	1150	4, 48	287	4.609	0.00314
	TASK*BATTERY	1826	16, 192	114	1.990	0.01550
LF:HF	TASK	812	4, 40	203	13.746	0.00000
	BATTERY	61	4, 40	15	2.471	0.05994
	TASK*BATTERY	167	16, 160	10	2.146	0.00879

Frequency spectra demonstrated fewer main effects between tasks. The general trend in the frequency components is similar to the time domain measures, where variability in both the low- and high-frequency bands increase over time. During *pre-test,* high-frequency power was significantly (*p*<0.05) higher in the *maze* task compared with all other tasks. No other task-related changes were observed in frequency spectra in this period. Physical activity reduced the variability on frequency spectra, however, as participant's time-on-task increased, this variability also increased. Conversely, the ratio between low- and high-frequency power decreases as time-on-task increases. Likewise, the relative percentage of low-frequency power (%LF [LF/HF]) decreases, however, this is only evident until the *identification* task. During the *one card-learning* task this variable increases and remains elevated into the last task (*one-back*) or decreases hereafter.

Table XXXI: Task-related changes in frequency spectra. Task presented in order of completion (all values mean ± SD).



FREQUENCY SPECTRA	PRE			CTB2			CTB 3			CTB 4			POST		
	Mean	SD		Mean	SD		Mean	SD		Mean	SD		Mean	SD	
GMLT															
HF Power (ms^2)	964	962	$^{b\,c\,d\,e}$	304	330		197	257		221	213		82	160	
LF Power (ms^2)	1927	1385		827	449	^{e}	770	643		836	676		334	514	
LF:HF Ratio	2.65	1.35		4.39	2.47		4.87	2.87		6.66	4.22	^{c}	6.64	4.56	
LF% [LF/HF]	70.3	10.0		77.7	9.71	^{c}	79.77	8.75		80.5	11.9		82.7	9.69	
VLF Power (ms^2)	---	---		---	---		---	---		---	---		---	---	
DET															
HF Power (ms^2)	1426	1328	^{a}	510	358		320	386		351	379		74	64.6	
LF Power (ms^2)	2213	1475		1197	837		1031	1017		1127	828		476	395	
LF:HF Ratio	2.62	1.68		2.62	1.13		3.88	1.37		5.39	3.98		8.04	3.63	
LF% [LF/HF]	66.3	14.4		70.3	7.70		77.7	7.50		79.6	9.84		87.1	5.32	
VLF Power (ms^2)	---	---		---	---		---	---		---	---		---	---	
IDENT															
HF Power (ms^2)	1550	1078	^{a}	514	323		309	378		272	253		116	98.0	
LF Power (ms^2)	2713	2226		1001	609		1033	956		859	772		620	558	
LF:HF Ratio	2.40	1.77		2.26	1.27		4.13	1.60		3.61	2.03	^{a}	8.61	5.22	^{e}
LF% [LF/HF]	62.9	17.9		65.1	12.6	^{a}	78.6	7.07		75.3	8.55		80.6	23.9	
VLF Power (ms^2)	---	---		---	---		---	---		---	---		---	---	
OCL															
HF Power (ms^2)	1783	1454	^{a}	612	461		354	513		380	490		145	126	
LF Power (ms^2)	2591	1872		1580	1027		1124	1041		1141	906		707	580	
LF:HF Ratio	2.25	1.76		2.96	1.33		4.35	2.00		4.33	1.71		6.94	5.45	
LF% [LF/HF]	62.1	16.4		72.0	9.32		78.6	8.44		79.0	7.81		83.6	7.00	
VLF Power (ms^2)	3280	3777		986	675		961	755		755	602		505	424	
OBT															
HF Power (ms^2)	1840	1654	^{a}	711	568		515	599		434	436		329	374	
LF Power (ms^2)	2791	2335		1911	1625	^{a}	1516	1284		1428	1116		1172	1021	
LF:HF Ratio	1.96	1.03		3.31	2.23		4.00	1.78		4.24	1.49		5.48	2.42	^{c}
LF% [LF/HF]	62.7	9.58		70.7	13.8		76.0	8.98		79.0	7.21		80.8	9.72	
VLF Power (ms^2)	---	---		---	---		---	---		---	---		---	---	

*Different ($p<0.05$) to : **a** = GMLT : **b** = DETEC : **c** = IDENT : **d** = OCL : **e** = OBT*

When relating to task performance (primary outcome variables) in each test battery, performance showed very little improvement. *Post-test*, the *detection*, *identification*, *one-back* and *one card-learning* task all demonstrated slower processing speed and negligible changes in accuracy. *Post-test* performance during the *maze* task displayed the highest error rates and heart rate variability was lowest. Therefore, despite higher cognitive workload (as evidenced in all cognitive tasks through heart rate variability) cognitive performance shows deterioration in performance and impaired (p<0.05) cognitive function during the *maze* task.

4.7 Summary

The prolonged batting period increased cardiovascular demand and the perceptions of effort. Batters became slower between the wickets over time, but managed to improve the accuracy with which they could hit the ball. Heart rate variability decreased between test batteries, with the lowest responses elicited *post-test*. Conversely, with increasing time-on-task heart rate variability also increased. Despite increased cognitive workload over time, visual attention, working memory and executive functions deteriorated after 30 overs of batting (Table XXXII).

Table XXXII: Performance summary of schoolboy batters.

		PRE vs. POST			**CTB 3 vs. POST**		
		△	**P value**	**Cohens d**	△	**P value**	**Cohens d**
BATTING PERFORMANCE	*Sprint Times*	↑	**< 0.01**	**0.84**	↑	**< 0.02**	**0.54**
	Batting Accuracy	↑	> 0.05	**0.63**	↑	> 0.05	0.11
PHYSIOLOGICAL PERFORMANCE	*Heart Rate*	↑	**< 0.01**	**0.91**	↑	**< 0.02**	**0.52**
	Mass - Fluid Balance	↓	**< 0.01**	0.09			
PERCEPTUAL RESPONSES	*RPE: Central*	↑	**< 0.01**	**2.49**	↑	**< 0.01**	**1.39**
	RPE: Local	↑	**< 0.01**	**2.37**	↑	**< 0.01**	**1.29**
COGNITIVE PERFORMANCE	*Heart Rate - Battery*	↑	**< 0.01**	**3.76**	↑	> 0.05	**0.45**
	Heart Rate - Task	↓	**< 0.01**				
	HRV: SDNN - Battery	↓	**< 0.01**	**2.61**	↓	> 0.05	**1.15**
	HRV: SDNN - Task	↑	**< 0.01**				
	HRV: rMSSD - Battery	↓	**< 0.01**	**2.60**	↓	> 0.05	**1.17**
	HRV: rMSSD - Task	↑	**< 0.01**				
	HRV: HF Power	↓	> 0.05	**0.79**	↓	> 0.05	0.01
	HRV: LF Power	↓	**< 0.01**	**1.88**	↓	> 0.05	**1.12**
	HRV: HF:LF Ratio	↑	**< 0.01**	**1.88**	↑	> 0.05	**1.00**
	HRV: HF$_{n.u.}$	↑	> 0.05	**1.89**	-	> 0.05	**1.03**
	HRV: LF$_{n.u.}$	↓	> 0.05	**1.89**	-	> 0.05	**1.03**
	Executive Function	↑	> 0.05	**0.58**	↑	> 0.05	0.14
	Psychomotor Function	↑	> 0.05	**0.37**	-	> 0.05	0.01
	Vigilance	↑	> 0.05	**0.56**	↑	> 0.05	**0.37**
	Visual Learning & Memory	↑	> 0.05	0.01	↓	> 0.05	**0.33**
	Attention & Working Memory	↓	> 0.05	**0.61**	↓	> 0.05	0.15

CHAPTER V - RESULTS: ACADEMY BATTERS - PHASE 2 & 3

5.1 Key Considerations for Statistical Interpretation

The following section highlights the main findings obtained from academy batters. Throughout this section, only main effects from *phase 2* (*test*) and *3* (*retest*) will be discussed. These will be presented together to allow comparison of results. In addition to the *time/stage, task* and *battery effects* established in *phase 1*, *condition effects* will also be referred to in this chapter.

- A *condition effect* refers to differences that are apparent between the *test* and *retest* sessions. Changes observed in this regard may suggest poor reliability and reproducibility of the results.

Unless otherwise stated, all statistical analyses were performed with a 95% confidence interval ($p<0.05$). Also, where appropriate, 'Cohen's *d*' was used to calculate the magnitude of effect.

5.2 Results Overview

Heart rate increased ($p<0.01$) in both conditions as the simulation progressed; however, a *condition effect* indicated that the *retest* condition elicited lower responses ($p<0.05$ - Table XXXIII). Similarly, mass decreased ($p<0.01$) over time, with the *retest* condition recording ($p<0.05$) higher weight loss than *test* condition. Both central and local RPE increased ($p<0.01$) over time. Central RPE was rated higher than local RPE in stage 2 only – this result was reproduced in the *retest* session. Sprint times slowed ($p<0.01$) over time and no *condition effects* were demonstrated. Within each condition, *task effects* for run type were also observed ($p<0.05$). There were no *time effects* observed for vertical jump, however, *task effects* for jump type demonstrated consistently higher countermovement jump height ($p<0.01$) compared to squat jump height.

During cognitive assessments, heart rate variability decreased ($p<0.01$) between batteries and increased ($p<0.01$) as time-on-task increased. The cognitive performance of academy batters was not impaired in any of the tasks, with visual learning and memory showing improved accuracy ($p<0.01$) over time.

Table XXXIII: Statistical overview of performance effects. (X – denotes a difference, where *p*<0.05 and XX denotes a difference, where *p*<0.01)

		TIME EFFECT	TASK EFFECT	BATTERY EFFECT	CONDITION EFFECT
PHYSIOLOGICAL PERFORMANCE	*Heart rate*	XX			X
	Mass - Fluid balance	XX			X
	Relative sweat loss				X
BATTING PERFORMANCE	*Sprint times*	XX	X		
	Vertical jump		XX		
PERCEPTUAL RESPONSES	*Central RPE*	XX			
	Local RPE	XX			
COGNITIVE PERFORMANCE	*Heart rate*		XX	XX	
	Heart Rate Variability		XX	XX	
	Maze Task				
	Detection				
	Identification				
	One Card-learning			XX	
	One Back				

5.3 Batting Performance

The distances covered by academy batters were the same as those covered by the schoolboy sample. Similarly, the high- and low-intensity efforts were the same. The total distances that academy batters completed during the *test* and *retest* sessions were; 3730.4 m, with 2280.8 m at a maximal intensity and 1449.8 m at low-intensity.

5.3.1 Sprint Times

Sprint times are comparable between conditions, with no *condition effects* observed in mean sprint times. *Time effects* were observed for mean sprint time and for run type (single, double and triple shuttle times), where in each condition batters slowed (*p*<0.01) over time (Table XXXV). Although not significant, mean sprint times in the *retest* condition were faster than those recorded during *test* (*p*=0.18). In both conditions, mean sprint times were faster in stage 2 compared to stage 6 (*test*: *d* = 0.70 and *retest*: *d* = 0.51- Figure 14).

Table XXXIV: Two-factorial ANOVA for sprint times, utilising condition and stage as factors.

Sprint Times		**SS**	**DoF**	**MS**	**F**	**p**
Average	CONDITION	0.027	1, 15	0.027	2.023	0.17542
	STAGE	0.065	2, 30	0.033	14.682	0.00004
	CONDITION*STAGE	0.003	2, 30	0.002	0.680	0.51426
Singles	CONDITION	0.027	1, 15	0.027	1.697	0.21238
	STAGE	0.143	2, 30	0.071	24.244	0.00000
	CONDITION*STAGE	0.003	2, 30	0.002	0.382	0.68588
Doubles	CONDITION	0.020	1, 15	0.020	2.281	0.15171
	STAGE	0.041	2, 30	0.021	5.249	0.01110
	CONDITION*STAGE	0.000	2, 30	0.000	0.037	0.96377
Triples	CONDITION	0.029	1, 15	0.029	8.290	0.01147
	STAGE	0.082	1, 15	0.082	24.534	0.00017
	CONDITION*STAGE	0.023	1, 15	0.023	5.120	0.03893
Fours	CONDITION	0.048	1, 15	0.048	1.648	0.21876
	STAGE	0.035	2, 30	0.018	2.416	0.10641
	CONDITION*STAGE	0.013	2, 30	0.007	0.867	0.43067

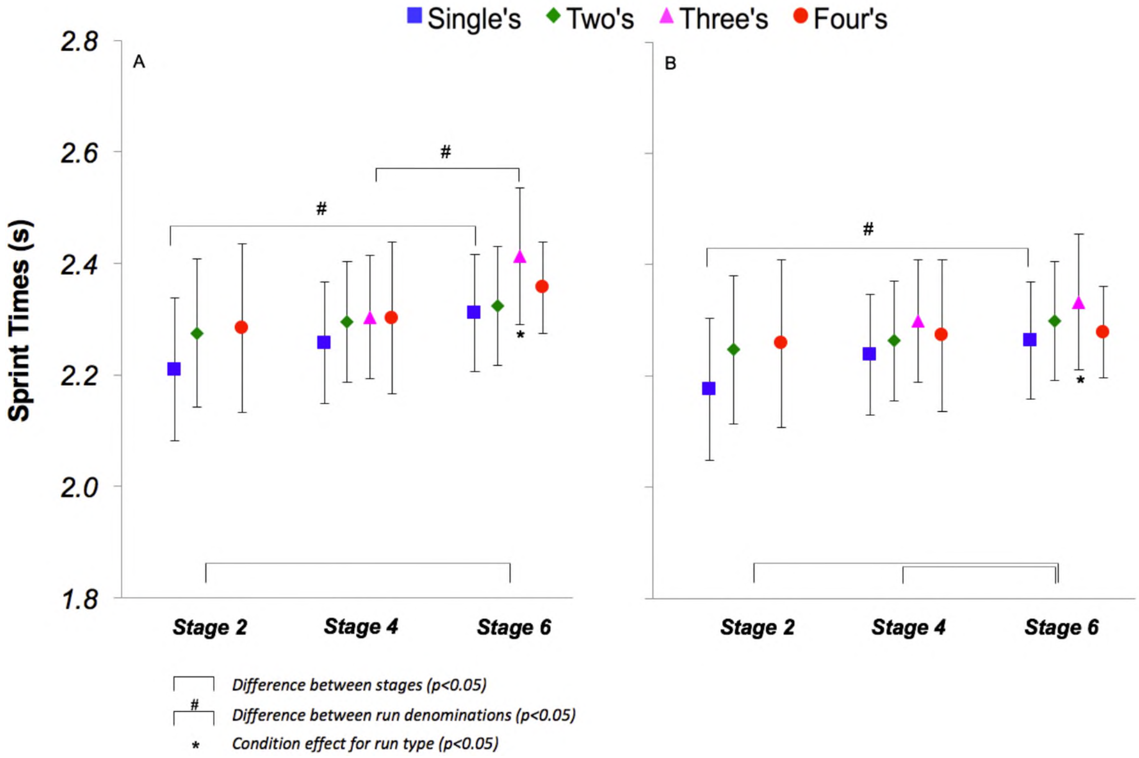


Figure 14: Mean (±SD) sprint times comparing mean and individual run type data in both conditions. A = *test* condition, B = *retest*.

In the *test* condition, the average time to complete a single was slower ($p<0.01$; $d = 0.86$) in stage 6 (2.311 ± 0.105 s) than stage 2 (2.210 ± 0.128 s). Also, triple shuttles were slower ($p<0.01$; $d = 0.94$) in stage 6 (2.413 ± 0.107 s) compared to 4 (2.304 ± 0.110 s).

Table XXXV: Between condition comparisons of mean sprint times during maximal stages (all values are mean ± SD).

	TEST			***RETEST***		
	Stage 2	*Stage 4*	*Stage 6*	*Stage 2*	*Stage 4*	*Stage 6*
MEAN ± SD	2.26 ± 0.119 ^{c}	2.29 ± 0.099	2.33 ± 0.089 ^{a}	2.23 ± 0.094 ^{c}	2.27 ± 0.114 ^{c}	2.28 ± 0.101 $^{a\,b}$
CV	5%	4%	4%	4%	5%	4%

Different (p<0.05) to : ***a*** = Stage 2 : ***b*** = Stage 4 : ***c*** = Stage **6** : † = Condition effect

Within the *retest* condition (Figure 14B), sprint times in stage 2 were faster than stage 6 (p<0.01; d = 0.80) and stage 4 (p<0.05; d = 0.39). Singles shuttle time was fastest (p<0.01; d = 1.32) in stage 2 (2.176 ± 0.100 s) compared to stage 6 (2.263 ± 0.121 s). No other differences were observed in the *retest condition.* The *condition effect* was observed in triple shuttles times, where mean sprint time in stage 6 (2.41 ± 0.122 s) of the *test condition* was slower (p<0.01) than times in stage 4 (2.30 ± 0.121 s; p<0.01; d = 0.94) and stage 6 (2.33 ± 0.110 s; p<0.02; d = 0.98) of the *retest condition*.

5.3.2 Vertical Jump Height

No *condition* or *time effects* are observed for vertical jump height (Table XXXVI). The only statistical effect observed occurred between jump types (*task effect*).

Table XXXVI: Three-factorial ANOVA for maximal jump height using, condition, pre-post and jump type as effects.

Vertical Jump Height	**SS**	**DoF**	**MS**	**F**	**p**
CONDITION	121.485	1, 15	121.485	3.373	0.08618
PRE-POST	0.963	1, 15	0.963	0.156	0.69809
JUMPTYPE	803.504	1, 15	803.504	125.156	0.00000
CONDITION*PRE-POST	1.643	1, 15	1.643	0.203	0.65907
CONDITIO*JUMPTYPE	2.448	1, 15	2.448	1.048	0.32219
PRE-POST*JUMPTYPE	0.034	1, 15	0.034	0.010	0.92151
CONDITION*PRE-POST*JUMPTYPE	0.513	1, 15	0.513	0.344	0.56617

Within the *test* condition, CMJ heights were higher than SJ heights for both *pre* (p<0.01; d = 0.99) and *post-test* (p<0.01; d = 1.07) comparisons. Batters attained maximal CMJ heights of 54.41 ± 5.11 cm before and 54.52 ± 4.30 cm after batting. For the same comparison, SJ heights were 49.84 ± 4.11 cm and 49.63 ± 4.81 cm, respectively. Results for the *retest* condition are comparable, with statistical interactions similar to those observed during *test*. Batters improved *post* protocol CMJ heights in both conditions and SJ height in the *retest* condition only (Figure 15). Effect sizes comparisons for the *retest* condition were; *pre* CMJ *vs. pre* SJ (*d* = 0.87) and *post* CMJ vs. *post* SJ (*d* = 0.89). No differences in the eccentric utilisation ratios for *pre* and *post-test* measures were observed (*p*>0.05). *Post-test* eccentric utilisation ratios of 1.10 ± 0.06 and 1.10 ± 0.05 were reported for the *test* and *retest* sessions.

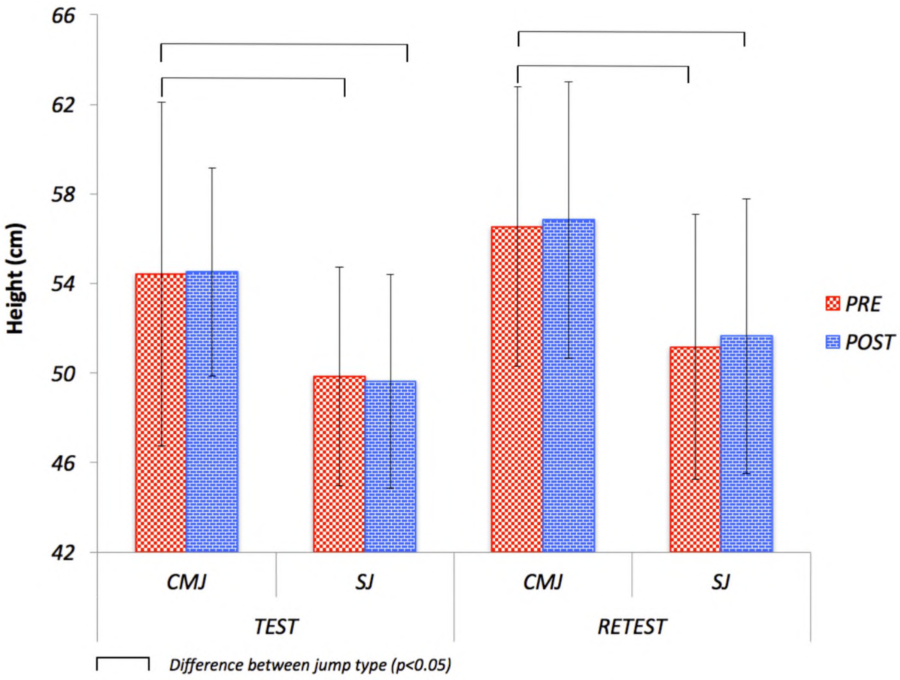


Figure 15: Maximal jump heights attained *pre* and *post* simulation (CMJ = countermovement jump and SJ = squat jump - all values mean ± SD).

The largest inter-individual variability is observed for *pre-test* CMJ jump height in the *test* session. Variability for all other jumps is comparable.

5.4 Physiological Responses

5.4.1 Heart Rate

Condition effects demonstrated that heart rates in stages, 1, 3, 5 and 6 were lower in the *retest* condition (Table XXXVII). A *time effect* in the *test* and *retest* sessions showed responses were higher in the maximal intensity stages of batting. Additionally, *over* effects and *interaction* effects (*stage***over*) were also found in both sessions.

Table XXXVII: Three-factorial ANOVA for heart rate responses, using condition, stage and over as effects.

Heart Rate	**SS**	**DoF**	**MS**	**F**	**p**
CONDITION	7540	1, 14	7540	5.178	0.03913
STAGE	79411	5, 70	15882	79.184	0.00000
OVER	13165	4, 56	3291	27.480	0.00000
CONDITION*STAGE	1951	5, 70	390	2.307	0.05337
CONDITION*OVER	539	4, 56	135	1.603	0.18623
STAGE*OVER	27392	20, 280	1370	13.026	0.00000
CONDITION*STAGE*OVER	2648	20, 280	132	1.309	0.17190

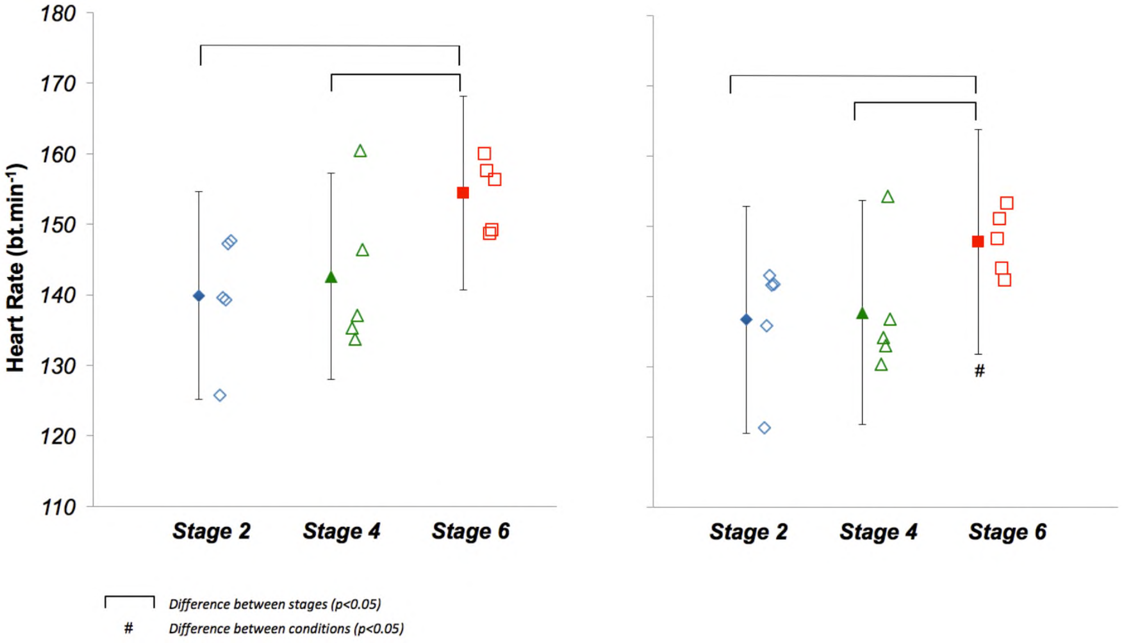


Figure 16: Comparison of mean (± SD) heart rate (single data point with error bar) and average heart rate per over (multiple, unfilled data points) between *test* and *retest*.

Heart rate in both conditions was highest in stage 6 compared to stages 2 (*test*: $p<0.01$*;* $d = 0.93$; *retest*: $p<0.01$; d = 0.61) and 4 (*test*: $p<0.01$; $d = 0.74$; *retest*: $p<0.01$; $d = 0.62$). Within each stage, heart rate increased ($p<0.05$) incrementally each over, with the highest heart rates attained in the fourth and fifth overs of each stage. Interestingly, the variability between overs was lowest in the final stage of each condition.

Table XXXVIII: Heart rate responses (bt.min^{-1}) of academy batters in response to 30 overs of intermittent batting (all values are mean ± SD while CV represents coefficient of variation).

	TEST					
	Stage 1	*Stage 2*	*Stage 3*	*Stage 4*	*Stage 5*	*Stage 6*
MEAN ± SD	127 ± 15.33 ^{bdef†}	140 ± 16.60 ^{acdf}	129 ± 17.22 ^{bdef†}	143 ± 17.44 ^{acf}	144 ± 16.08 ^{acf†}	154 ± 14.34 ^{abcdef†}
CV	12%	12%	13%	12%	11%	9%
	RETEST					
	Stage 1	*Stage 2*	*Stage 3*	*Stage 4*	*Stage 5*	*Stage 6*
MEAN ± SD	119 ± 15.90 ^{acdf}	137 ± 17.82 ^{acf}	121 ± 18.52 ^{bdef†}	138 ± 17.96 ^{acf}	134 ± 16.29 ^{acf†}	148 ± 16.15 ^{abcdef†}
CV	13%	13%	15%	13%	12%	11%

*Different ($p<0.05$) to : **a** = Stage 1 : **b** = Stage 2 : **c** = Stage 3 : **d** = Stage 4 : **e** = Stage 5 : **f** = Stage 6 : † = Condition effect*

5.4.2 Fluid Balance and Sweat Loss

Given the extended duration of *phase* 2 and 3, mass was rerecorded on both days of experimentation (*pre* and *post-test*). From this, fluid balance and sweat loss were calculated.

Table XXXIX: Three-factorial ANOVA for body mass.

Body Mass	**SS**	**DoF**	**MS**	**F**	**p**
CONDITION	11.520	1, 15	11.520	6.027	0.02678
KIT	419.775	1, 15	419.775	2036.303	0.00000
PRE-POST	8.611	1, 15	8.611	24.763	0.00017
CONDITION*KIT	0.080	1, 15	0.080	2.233	0.15587
CONDITION*PRE-POST	0.008	1, 15	0.008	0.115	0.73930
KIT*PRE-POST	0.361	1, 15	0.361	15.427	0.00134
CONDITION*KIT*PRE-POST	0.025	1, 15	0.025	1.126	0.30541

In both conditions player's body mass decreased ($p<0.01$) over time (*test*: d = 0.07: *retest*: d = 0.42 - Table XL). *Condition effects* illustrate weight loss was higher ($p<0.01$; d = 0.09) during *retest* (0.87%) compared to the *test* condition (0.75%). Similarly, relative sweat loss ($p<0.01$; d = 0.09) and rate of sweat loss were higher during *retest* (1.33 ± 0.13 %BM and 0.36 ± 0.04 L.h^{-1}, respectively) compared to *test* (1.32 ± 0.14 %BM and 0.36 ± 0.04 L.h^{-1}). During *test*, players consumed an average of 1.11 L of water at 0.32 L.h^{-1}, whereas during *retest*, water consumption was 1.02 L at 0.29 L.h^{-1}.

Table XL: Mass and fluid loss in response to 30 overs of intermittent activity (all values are mean ± SD while CV represents coefficient of variation).

	TEST				RETEST			
Mass (kg)	Without Kit		With Kit		Without Kit		With Kit	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
MEAN ± SD	77.36 ± 8.12	76.78 ± 7.82 ^{a}	80.85 ± 8.02	80.43 ± 7.88 ^{ab}	76.76 ± 7.54	76.09 ± 7.27 ^{a}	80.29 ± 7.57	79.89 ± 7.32 ^{ab†}
CV	10%	10%	10%	10%	10%	10%	9%	9%

Fluid loss	Relative Sweat Loss (% BM)		Relative Rate of Sweat Loss ($L.h^{-1}$)		Relative Sweat Loss (% BM)		Relative Rate of Sweat Loss ($L.h^{-1}$)	
	Without Kit	With Kit	Without Kit	With Kit	Without Kit	With Kit	Without Kit	With Kit
MEAN ± SD	1.32 ± 0.14	1.25 ± 0.13 ^{b}	0.36 ± 0.04	0.34 ± 0.03 ^{b}	1.33 ± 0.13	1.26 ± 0.12 ^{b†}	0.36 ± 0.04	0.34 ± 0.03 ^{b†}
CV	11%	11%	11%	10%	10%	10%	10%	9%

a = time effect : b = effect of kit : † = condition effect

5.5 Perceptual Responses

No *condition effects* were observed for ratings of perceived exertion (RPE) despite batters rating the *retest* condition lower. *Stage* and *over effects* were observed for both central and local RPE (Table XLI). Additionally, batters consistently rated central RPE higher than local RPE, however, this was only significant (p<0.02) in stage 2.

Table XLI: Statistical interactions (three-factorial ANOVA) for ratings of perceived exertion.

Ratings of Perceived Exertion		SS	DoF	MS	F	p
Central RPE	CONDITION	71	1, 14	70.560	3.116	0.09933
	STAGE	3395	5, 70	679.087	84.740	0.00000
	OVER	264	4, 56	66.043	52.587	0.00000
Local RPE	CONDITION	29	1, 14	29.160	2.441	0.14055
	STAGE	3932	5, 70	786.379	92.878	0.00000
	OVER	217	4, 56	54.296	51.522	0.00000
Central vs. Local RPE	CONDITION	9.74	1, 15	9.743	1.762	0.20424
	CEN-LOC	7.86	1, 15	7.861	7.451	0.01551
	STAGE	484	2, 30	242.072	92.255	0.00000

As with heart rate, both central and local RPE increased (p<0.05) over time (Figure 17). *Time effects* were observed for both conditions and in both RPE measures. In the *test* condition, central and local ratings were highest in stage 6 compared to stages 2 (central: p<0.01; d = 1.91 and local: p<0.01; d = 2.19) and 4 (central: p<0.01; d = 1.10 and local p<0.01; d = 1.30). Additionally, both central and local RPE in stage 4 were higher than ratings in stage 2 (central: *p*<0.01; *d* = 0.77 and local: *p*<0.01; d = 1.09). These results were replicated in *retest* condition; stage 6 vs. 2 (central: *p*<0.01; *d* = 2.24 – local *p*<0.01; *d* = 2.81); stage 6 vs. 4 (central: *p*<0.01; *d* = 1.24 and local: *p*<0.01; *d* = 1.65) and stage 4 vs. 2 (central: *p*<0.01; *d* = 1.03 and local: *p*<0.01; *d* = 1.04).

Table XLII: Central and local ratings of perceived exertion as per condition (all values are mean ± SD).

			TEST			
CENTRAL	*Stage 1*	*Stage 2*	*Stage 3*	*Stage 4*	*Stage 5*	*Stage 6*
MEAN ± SD	9.16 ± 1.56 ^{bcdef}	11.33 ± 1.75 ^{bdef}	10.81 ± 1.71 ^{adef}	12.76 ± 2.00 ^{abcf}	13.00 ± 1.61 ^{abcf}	15.01 ± 2.10 ^{abcde}
CV	17%	15%	16%	16%	12%	14%
LOCAL	*Stage 1*	*Stage 2*	*Stage 3*	*Stage 4*	*Stage 5*	*Stage 6*
MEAN ± SD	8.59 ± 1.70 ^{bcdef}	10.40 ± 1.79 ^{adef}	10.48 ± 1.53 ^{adef}	12.28 ± 1.64 ^{abcf}	14.18 ± 11.41 ^{abcf}	14.81 ± 2.22 ^{abcde}
CV	20%	17%	15%	13%	11%	15%
			RETEST			
CENTRAL	*Stage 1*	*Stage 2*	*Stage 3*	*Stage 4*	*Stage 5*	*Stage 6*
MEAN ± SD	7.86 ± 1.46 ^{bcdef}	10.20 ± 2.22 ^{adef}	10.41 ± 2.00 ^{adef}	12.29 ± 2.15 ^{abcf}	12.61 ± 1.81 ^{abcf}	14.86 ± 2.33 ^{abcde}
CV	19%	22%	19%	18%	14%	16%
LOCAL	*Stage 1*	*Stage 2*	*Stage 3*	*Stage 4*	*Stage 5*	*Stage 6*
MEAN ± SD	7.65 ± 1.29 ^{bcdef}	9.56 ± 1.95 ^{adef}	10.05 ± 1.83 ^{adef}	12.01 ± 1.85 ^{abcf}	12.84 ± 1.41 ^{abcf}	14.74 ± 1.86 ^{abcde}
CV	17%	20%	18%	15%	11%	13%

*Different (p<0.05) to : **a** = Stage 1 : **b** = Stage 2 : **c** = Stage 3 : **d** = Stage 4 : **e** = Stage 5 : **f** = Stage 6 : † = Condition effect*

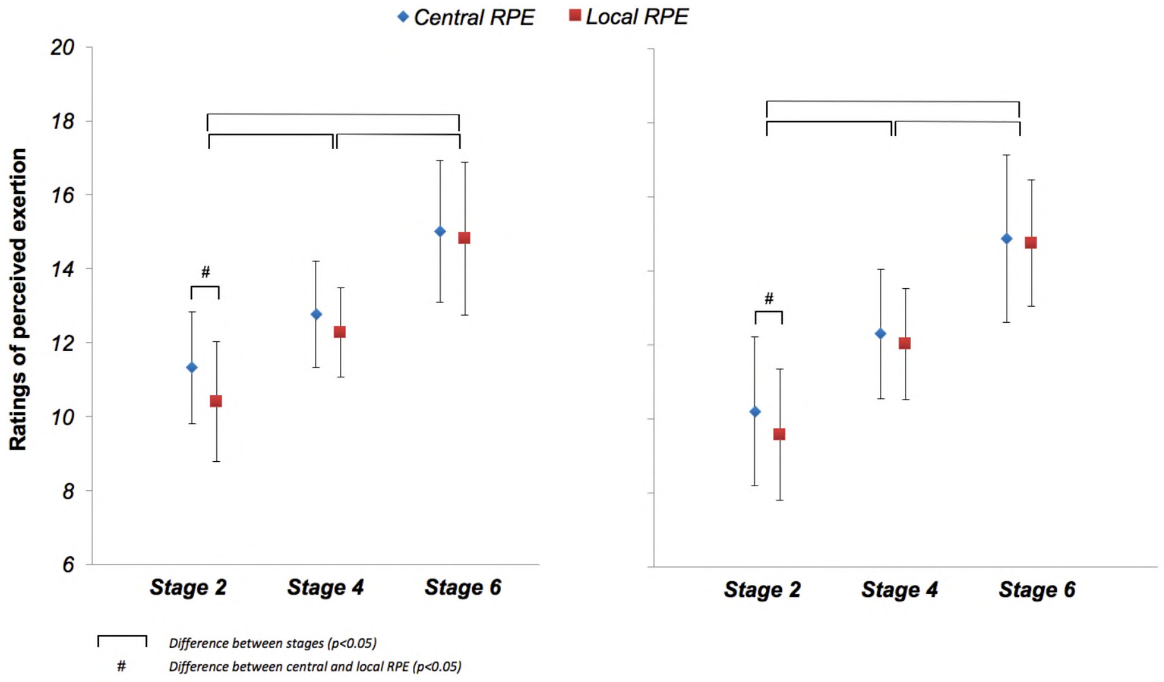


Figure 17: Central and local ratings of perceived exertion during maximal intensity stages (all values mean ± SD).

5.6 Cognitive Performance

The primary outcome variables are the same as those for *phase 1*. Where appropriate, the terms *pre*, *during* and *post* are synonymous with *CTB 1*, *2* and *3*.

5.6.1 Time-On-Task

Table XLIII: Statistical Interactions for time-on-task within and between the test and retest sessions.

Time-on-Task		**SS**	**DoF**	**MS**	**F**	**p**
Maze	CONDITION	19551	1, 15	19551	13.883	0.00203
	BATTERY	25558	2, 30	12779	19.273	0.00000
Detection	CONDITION	1001	1, 15	1001	8.121	0.01217
	BATTERY	5039	2, 30	2520	14.717	0.00004
Identification	CONDITION	284	1, 15	284	1.304	0.27139
	BATTERY	229	2, 30	114	0.856	0.43480
One card-learning	CONDITION	2604	1, 15	2604	3.433	0.08369
	BATTERY	4842	2, 30	2421	4.233	0.02402
One-back	CONDITION	21	1, 15	21	0.208	0.65525
	BATTERY	258	2, 30	129	0.841	0.44125
Total Duration	CONDITION	50876	1, 15	50876	43.840	0.00001
	BATTERY	87248	2, 30	43624	35.707	0.00000

A *battery effect* for total cognitive test duration showed that *time-on-task* decreased from *pre-* to *post-test* (p<0.01) in both the *test* and *retest* condition. Mean *pre-test* battery duration during in the *test* condition 00:17:34 ± 00:01:08 (hh:mm:ss) was longer than the second (p<0.01 -00:16:25 ± 00:01:04) and final test battery (00:16:04 ± 00:01:10 – p<0.01). In contrast, during *retest*, participants required only 00:16:24 ± 00:01:14, 00:15:51 ± 00:01:08 and 00:15:30 ± 00:01:10 to complete each battery. Here, a *battery effect* was only observed between *pre* and *post-test*.

Additionally, a *condition effect* indicated that the amount of time required to complete each test battery was longer (p<0.05) during *test* compared to *retest*. The *maze* and *detection* tasks were the only two tasks to show *condition effects* for time on task. In both tasks, batters were faster over time (p<0.05) and in *retest* session when compared to the *test* condition. These differences can be partly associated with task familiarisation and a decreasing reliance on task instructions presented before each task.

5.6.2 Primary Outcome Variables

No *condition effects* were observed in speed of processing. A *battery effect* was demonstrated in *retest* condition for *one card-learning* speed only (Table XLIV). No other main effects were found for speed of processing. In the *test* condition a small improvement (*p*=0.55; *d* = 0.27) in *one-back* speed was observed between *pre* and *post-test,* while a moderate improvement in *one card-learning* speed (*p*=0.15; *d* = 0.50) was observed over the same period (Figure 18).

Table XLIV: Two-factorial analysis of variance during the *detection*, *identification*, *one-card learning* and *one-back* tasks.

Speed of Processing		**SS**	**DoF**	**MS**	**F**	**p**
Detection	CONDITION	0.003	1, 15	0.003	0.489	0.49498
	BATTERY	0.009	3, 45	0.003	0.493	0.68867
	CONDITION*BATTERY	0.011	3, 45	0.004	2.031	0.12307
Identification	CONDITION	0.003	1, 15	0.003	0.969	0.34045
	BATTERY	0.006	3, 45	0.002	0.736	0.53596
	CONDITION*BATTERY	0.010	3, 45	0.003	1.905	0.14241
One card-learning	CONDITION	0.006	1, 15	0.006	2.106	0.16734
	BATTERY	0.030	3, 45	0.010	3.429	0.02481
	CONDITION*BATTERY	0.003	3, 45	0.001	0.804	0.49847
One-back	CONDITION	0.001	1, 15	0.001	0.186	0.67244
	BATTERY	0.013	3, 45	0.004	1.235	0.30822
	CONDITION*BATTERY	0.001	3, 45	0.000	0.189	0.90337

During *retest*, *post-test* processing speed for the *one card-learning* task was faster (*p*<0.04; *d* = 0.61) compared to *pre-test* and baseline (*p*<0.03; *d* = 0.67). Small improvements were observed between *pre* and *post-test* in the *detection* (*p*=0.42; *d* = 0.27), *identification* (*p*=0.99; *d* = 0.32) and *one-back* tasks (*p*=0.55; *d* = 0.27). Small improvements were also shown between *during* and *post-test* in the *detection* (*d* = 0.27), *identification* (*d* = 0.31), *one-back* (*d* = 0.27) and *one card-learning* tasks (*d* = 0.33) – none of these improvements were statistically significant (*p*>0.05). Collectively, processing speeds improved with batting activity but lack statistical underpinning.

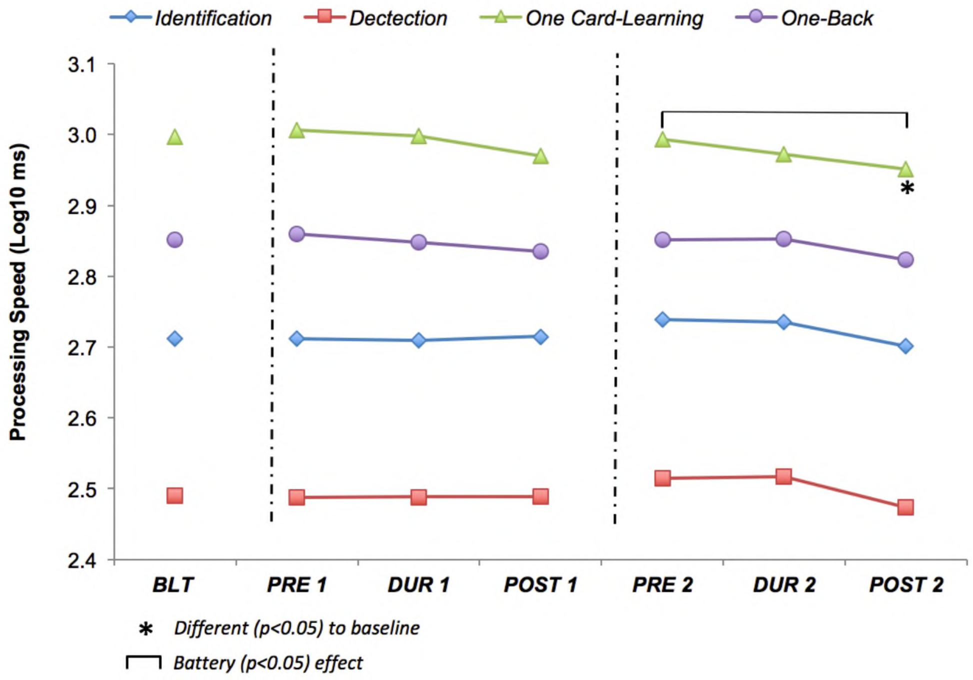


Figure 18: Mean processing speeds during the *identification*, *detection*, *one card-learning* and *one-back* task: *BLT = baseline, PRE = pre-test, DUR = after 15 overs, POST = post-test, 1 = test, 2 = retest.*

Table XLV: Primary outcome measures during *test* and *retest* (response time = $\log^{10}$ms, accuracy = arcsine proportion correct, all values mean ± SD).

			TEST						***RETEST***					
	BLT		***PRE***		***DUR***		***POST***		***PRE***		***DUR***		***POST***	
	Mean	***SD***	***Mean***	***SD***	***Mean***	***SD***	***Mean***	***SD***	***Mean***	***SD***	***Mean***	***SD***	***Mean***	***SD***
DETEC														
Response Time	2.49	0.09	2.49	0.08	2.49	0.12	2.49	0.12	2.51	0.16	2.52	0.18	2.47	0.14
Accuracy	1.43	0.11	1.44	0.14	1.42	0.14	1.43	0.16	1.43	0.13	1.44	0.14	1.42	0.10
IDENT														
Response Time	2.71	0.09	2.71	0.08	2.71	0.13	2.71	0.09	2.74	0.13	2.74	0.12	2.70	0.10
Accuracy	1.40	0.11	1.37	0.15	1.38	0.13	1.40	0.14	1.41	0.15	1.44	0.13	1.42	0.12
OBT														
Response Time	2.85	0.08	2.86	0.09	2.85	0.08	2.84	0.09	2.85	0.10	2.85	0.09	2.82	0.10
Accuracy	1.31	0.13	1.35	0.13	1.33	0.17	1.36	0.15	1.34	0.16	1.35	0.14	1.32	0.18
OCL														
Response Time	3.00	0.07	3.01	0.08 ^{g}	3.00	0.09 ^{g}	2.97	0.06	2.99	0.07 ^{g}	2.97	0.06	2.95	0.07 ^{abce}
Accuracy	0.97	0.14	1.03	0.13	1.06	0.11 ^{a}	1.05	0.12 ^{a}	1.04	0.14	1.08	0.14 ^{a}	1.04	0.17 ^{a}
GMLT														
Speed (mvs.s^{-1})	0.88	0.21	0.83	0.12 ^{defg}	0.89	0.16 ^{g}	0.97	0.20 ^{b}	0.93	0.18 ^{bg}	0.93	0.22 ^{bg}	1.06	0.20 ^{abcef}
Errors	42.94	19.97	40.44	17.53	38.06	15.99	40.81	13.66	35.88	15.47	39.75	13.49	33.81	9.86 ^{a}

Different (p<0.05) to : ***a*** = baseline : ***b*** = *PRE 1 :* ***c*** = *DUR 1 :* ***d*** = *POST 1 :* ***e*** = *PRE 2 :* ***f*** = *DUR 2 :* ***g*** = *POST 2 :* **†** = *condition effect*

No *condition effects* for accuracy were observed between *test* and *retest* sessions. When compared to baseline measures, the *battery effect* demonstrated that *one card-learning* accuracy improved over time (Table XLVI). Highest accuracy was associated with the *detection* and *identification* (simple) tasks, followed by the *one-back* and *one card-learning* tasks (Figure 19).

Table XLVI: Two-factorial ANOVA for accuracy rates during the *detection*, *identification*, *one card-learning* and *one-back* tasks, using condition and battery as effects.

Accuracy		**SS**	**DoF**	**MS**	**F**	**p**
Detection	CONDITION	0.000	1, 15	0.000	0.017	0.89837
	BATTERY	0.001	3, 45	0.000	0.014	0.99769
	CONDITION*BATTERY	0.004	3, 45	0.001	0.284	0.83694
Identification	CONDITION	0.028	1, 15	0.028	3.062	0.10056
	BATTERY	0.008	3, 45	0.003	0.146	0.93170
	CONDITION*BATTERY	0.015	3, 45	0.005	0.390	0.76052
One card-learning	CONDITION	0.002	1, 15	0.002	0.367	0.55373
	BATTERY	0.161	3, 45	0.054	6.652	0.00082
	CONDITION*BATTERY	0.004	3, 45	0.001	0.309	0.81876
One-back	CONDITION	0.001	1, 15	0.001	0.191	0.66834
	BATTERY	0.025	3, 45	0.008	0.395	0.75717
	CONDITION*BATTERY	0.014	3, 45	0.005	0.463	0.70980

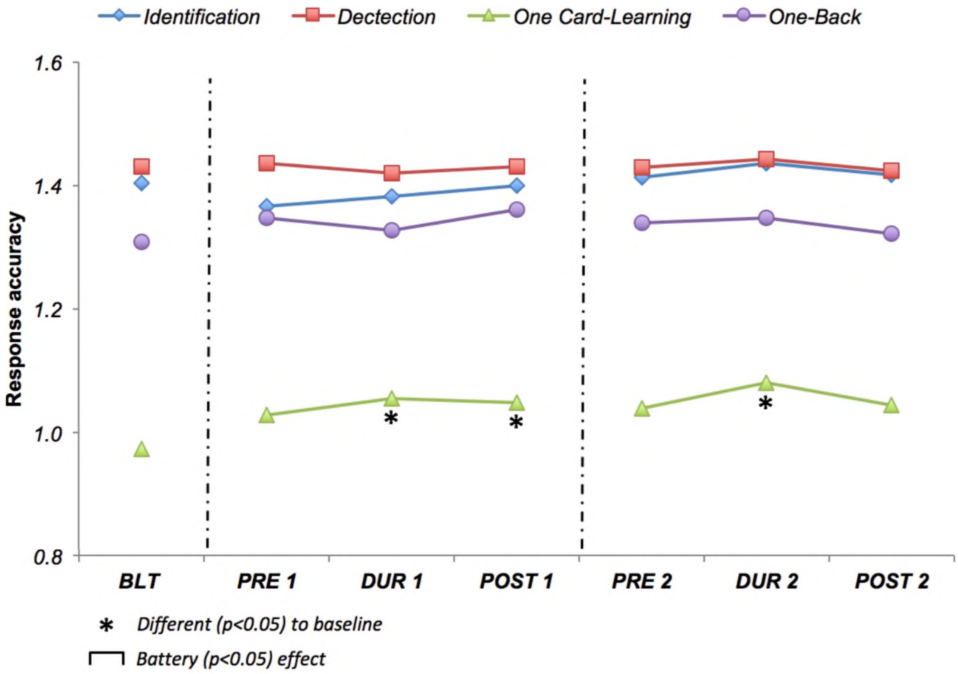


Figure 19: Mean accuracy responses (arcsine proportion correct) during the *identification*, *detection*, *one card-learning* and *one-back* tasks: *BLT = baseline, PRE = pre-test, DUR = after 15 overs, POST = post-test 1 = test, 2 = retest.*

In the *test* condition, an *effect of time* was observed in the *one card-learning* task, where, compared to *baseline*, accuracy improved *during* (*p*<0.02; *d* = 0.65) and *post-test* (*p*<0.04; *d* = 0.58). No other main effects were found in the *test* condition, however, a small effect for improved accuracy was observed in the *identification* task (*p*=0.83; *d* = 0.23). In the *retest* condition, accuracy in the *one-card-learning task* was also improved after 15 overs (during) compared to baseline (*p*<0.01; *d* = 0.76) with a small effect demonstrated between *pre* and *post-test* (*p*=0.99; *d* = 0.24) and between *pre* and *during* (*p*=0.46; *d* = 0.30).

A *condition effect* was observed for speed responses in the maze task, with batters recording faster speeds (*p*<0.01) during *retest*. Also, *battery effects* were found for processing speed as well as rule-break errors. An interaction effect was the only effect found in the primary outcome measure (error rates) for *maze* performance (Table XLVII).

Table XLVII: Statistical interactions of the Groton maze-learning task, *Condition* and battery used as effects in a two-factorial ANOVA.

Maze		SS	DoF	MS	F	p
Total Errors	CONDITION	195.031	1, 15	195.031	3.404	0.08488
	BATTERY	596.531	3, 45	198.844	1.848	0.15210
	CONDITION*BATTERY	386.281	3, 45	128.760	2.825	0.04925
Mvs.s^{-1}	CONDITION	0.122	1, 15	0.122	9.797	0.00688
	BATTERY	0.386	3, 45	0.129	7.373	0.00040
	CONDITION*BATTERY	0.057	3, 45	0.019	2.399	0.08033
Legal Errors	CONDITION	185.281	1, 15	185.281	5.161	0.03825
	BATTERY	220.031	3, 45	73.344	0.957	0.42145
	CONDITION*BATTERY	254.281	3, 45	84.760	2.758	0.05316
Rule-Break Errors	CONDITION	0.195	1, 15	0.195	0.013	0.90965
	BATTERY	104.461	3, 45	34.820	3.031	0.03891
	CONDITION*BATTERY	33.148	3, 45	11.049	1.183	0.32677

Pre and *post* comparisons showed that participants navigated through the maze faster over time in each condition (*test*: *p*<0.01; *d* = 0.80; and *retest*: *p*<0.01; *d* = 0.67). The number of moves per second in *test* condition increased from 0.88 ± 0.21 mvs.s^{-1} at *pre-test* to 0.97 ± 0.20 mvs.s^{-1} *post-test*. Similarly, the responses during *retest* were 0.93 ± 0.18 mvs.s^{-1} and 1.06 ± 0.19 mvs.s^{-1}, respectively. A small and moderate improvement in speed was also observed when comparing *during* and *post-test* in the *test* (*p*<0.18; *d* = 0.42) and *retest* conditions (*p*<0.02; *d* = 0.62 - Figure 20).

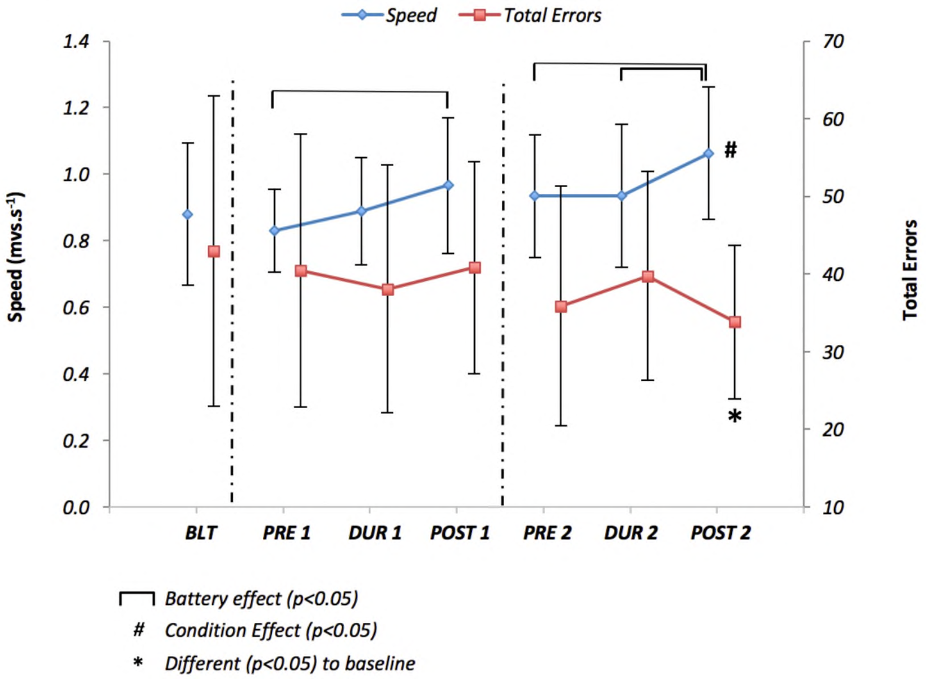


Figure 20: Mean (± SD) speed (moves per second) and error rates during the *maze* task: BLT = baseline, PRE = before batting, DUR = after 15 overs, POST = post simulation (30 overs), 1 = *test*, 2 = *retest.*

Despite increases in *maze* speed, error rates were unchanged ($p>0.05$) in both the *test* and *retest* conditions. Mean error rates were lower in the *retest* condition when compared to the *test* condition ($p>0.05$). Error rates in the *test* condition between *pre* and *during*, decline from 40.44 ± 17.53 to 38.07 ± 15.99; hereafter, error rates increased to 40.81 ± 13.66 (*during* vs. *post*). In the *retest* condition, the error rate function was inverted, where errors were highest after 15 overs of batting (39.75 ±13.49), whereafter batters accuracy improved (33.81 ± 9.86- $p=0.22$; $d = 0.50$). Compared to *baseline,* error rates in the retest session were significantly lower *post-test* ($p<0.03$; $d = 0.58$).

The majority of errors made in each battery are legal, with rule-break errors accounting for 12.52% (*pre-test*), 9.52% (*during*) and 11.33% (*post-test*) during the *test* condition (Figure 21). Similarly, *retest* rule-break error distributions were 10.45%, 13.05% and 13.86%, respectively.

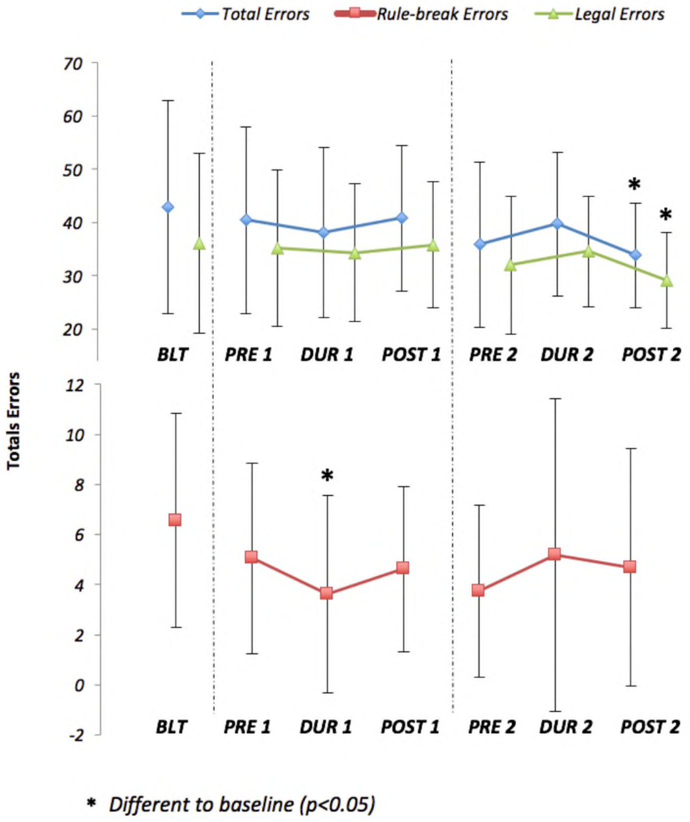


Figure 21: Mean (± SD) error rates and error types obtained during the maze task: BLT = baseline, PRE = before batting, DUR = after 15 overs, POST = post-simulation (30 overs), 1 = *test*, 2 = *retest*.

As with total error rates presented in Figure 20, *test* and *retest* rule-break error functions are different. In the *test* condition, the trend demonstrates decreasing rule-break error rates, with *pre-test* recording the highest number of errors (5.06 ± 3.80), followed by *post-test* 4.63 ± 3.30 (Figure 21). Contrastingly, during *retest*, rule-break errors were highest after 15 overs, 5.19 ± 6.24 followed by *post-tes*t rule-break error rates (4.69 ± 4.74). A small effect for reduced rule-break errors was observed between *pre-test* and *during* (*p*=0.39; *d* = 0.37). Also, when compared to baseline, rule break error rates *during* and *post-test* in the *test* condition were lower (*p*=0.01; *d* = 0.71 and *p*=0.16; *d* = 0.51, respectively). These results suggest that 15-overs of batting improves decision-making. This result was not replicated in the *retest* condition, where a small effect for increased rule-break errors was observed *during* (*p*=0.70; *d* = 0.29) and *post-test* (*p*=0.50; *d* = 0.23).

Variability in error types indicates that participant variability between test batteries is highest for rule-break errors compared to legal and total error counts. The greatest variability is notable in the second assessment (after 15 overs) in each condition. Coefficient of variation calculated for each test battery is as follows; 75%, 109% and 71% for *test*; and 92%, 120% and 101% during *retest*. When compared to the coefficient of variation for total errors, results are as follows, 43%, 42% and 33% calculated for *test* and 43%, 34% and 29% for *retest*.

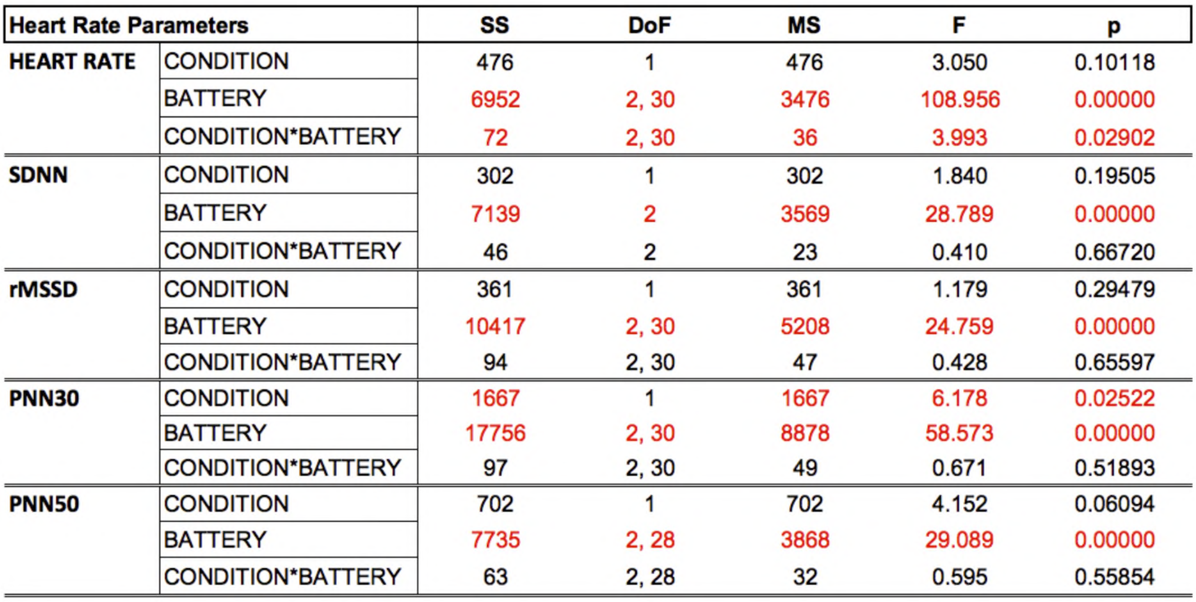
5.6.3 Heart Rate and Heart Rate Variability

The subsequent section details battery-related changes (differences in responses between cognitive test batteries), followed by task-related changes (differences in responses between individual tasks).

5.6.3.1 Battery-Related Differences

Battery effects were evident for all time domain parameters during cognitive assessment. Additionally, one *condition effect* (PNN30) and one *interaction effect* (heart rate) were also found (Table XLVIII).

Table XLVIII: Two-factorial ANOVA of time domain parameters of heart rate variability.



Heart Rate Parameters		SS	DoF	MS	F	p
HEART RATE	CONDITION	476	1	476	3.050	0.10118
	BATTERY	6952	2, 30	3476	108.956	0.00000
	CONDITION*BATTERY	72	2, 30	36	3.993	0.02902
SDNN	CONDITION	302	1	302	1.840	0.19505
	BATTERY	7139	2	3569	28.789	0.00000
	CONDITION*BATTERY	46	2	23	0.410	0.66720
rMSSD	CONDITION	361	1	361	1.179	0.29479
	BATTERY	10417	2, 30	5208	24.759	0.00000
	CONDITION*BATTERY	94	2, 30	47	0.428	0.65597
PNN30	CONDITION	1667	1	1667	6.178	0.02522
	BATTERY	17756	2, 30	8878	58.573	0.00000
	CONDITION*BATTERY	97	2, 30	49	0.671	0.51893
PNN50	CONDITION	702	1	702	4.152	0.06094
	BATTERY	7735	2, 28	3868	29.089	0.00000
	CONDITION*BATTERY	63	2, 28	32	0.595	0.55854

Compared to *pre-test* measures, heart rate was higher *during* (*p*<0.01) and *post-test* (*p*<0.01) in both the *test* (*d* = 1.58 and 2.22, respectively) and *retest* sessions (*d* = 1.14 and 2.11, respectively - Table XLIX). Similarly, moderate and large increases were observed for heart rate when comparing *during* and *post-test* responses in the *test* (*p*<0.01; *d* = 0.61) and *retest* sessions (*p*<0.01; *d* = 0.97). No *condition effects* were evident for SDNN, RMSSD and PNN50.

Table XLIX: Battery-related changes in time domain parameters of heart variability recorded during *test* and *retest* (all values are mean ± SD).

	TEST									***RETEST***								
	PRE			***DUR***			***POST***			***PRE***			***DUR***			***POST***		
	Mean	***SD***		***Mean***	***SD***		***Mean***	***SD***		***Mean***	***SD***		***Mean***	***SD***		***Mean***	***SD***	
HR (bt.min^{-1})	74	9.10	^{bcef}	88	9.66	^{acde}	94	9.56	^{abde}	70	7.98	^{bcef}	82	11.2	^{abcdf}	91	11.8	^{acde}
SDNN (ms)	44.8	17.3	^{bcef}	27.3	7.02	^{ad}	25.5	8.33	^{ad}	47.9	12.8	^{bcef}	32.8	13.1	^{ad}	27.7	9.65	^{ad}
rMSSD (ms)	57.9	23.4	^{bcef}	36.3	8.92	^{ad}	35.0	12.0	^{ad}	61.2	16.9	^{bcef}	42.8	17.0	^{ad}	36.8	12.1	^{ad}
PNN30 (%)	43.9	18.7	^{bcef}	20.8	14.3	^{ade}	12.0	8.74	^{ade}	51.8	16.0	^{bcef}	31.7	18.7	^{abcdf}	18.1	14.4	^{ade}
PNN50 (%)	25.3	16.8	^{bcef}	8.26	7.87	^{ad}	4.58	4.17	^{ade}	31.2	15.1	^{bcef}	15.2	14.2	^{acd}	7.79	8.11	^{ad}

Different (p<0.05) to : ***a*** *= PRE 1 :* ***b*** *= DUR 1 :* ***c*** *= POST 1 :* ***d*** *= PRE 2 :* ***e*** *= DUR 2 :* ***f*** *= POST 2 :* **†** *= condition effect*

Collectively, both SDNN and RMSSD decreased over time and displayed similar statistical effects throughout, as such, only RMSSD results will be reported. RMSSD decreased over time in both the *test* (*p*<0.01; *d* = 1.23) and *retest* conditions (*p*<0.01; *d* = 1.44 - Table XLIX). No differences were observed between *during* and *post-test* in either condition (*p*>0.05). A small decrease in RMSSD was, however, found in the *retest* condition (*d* = 0.36) between overs 15 and 30. A *condition effect* was observed for PNN30, where *retest* responses were, on average, higher than in the *test* condition (*p*<0.03). While the effects for PNN30 were the same as RMSSD, an additional *battery effect* between *during* and *post-test* was observed in the *retest* condition only: where PNN30 was lower (*p*<0.01; *d*= 0.78) *post-test* compared to after 15 overs.

Noteworthy, the inter-individual variability within heart rate variability decreases as the duration of batting increased, with *pre-test* measures recording the greatest variability and *post-test* the least variability (Table XLIX). This result was not evident in heart rate responses, where variability increased over time. Effect size comparisons are displayed in (Table L).

Table L: Time domain effect size comparisons (0.2-0.49 = small; 0.5-0.79 = moderate; >0.8 = large).

	PRE 1 vs. DUR 1	PRE 1 vs. POST 1	DUR 1 vs. POST 1	PRE 2 vs. DUR 2	PRE 2. vs. POST 2	DUR 2 vs. POST 2
HR	1.58	2.22	0.61	1.14	2.11	0.97
SDNN	1.33	1.42	0.24	1.17	1.56	0.39
rMSSD	1.22	1.23	0.12	1.08	1.44	0.36
PNN30	1.39	2.18	0.74	1.15	1.93	0.78
PNN50	1.30	1.69	0.58	1.09	1.59	0.51

Within the frequency spectrum comparisons, all components except low-frequency power yielded *battery effects* (Table LI). These effects showed decreases in the frequency spectra over time, with lowest responses observed *post-test* (Table LII). Compared to *pre-test,* high-frequency power was lowest *post-test* in both conditions (*test*: $p<0.02$; d = 0.92 and *retest*: $p<0.02$; d = 1.07).

Table LI: Two-factorial ANOVA of frequency spectrum components of heart rate variability.

Heart Rate Parameters		SS	DoF	MS	F	p
HF POWER	CONDITION	400879	1, 15	400879	1.472	0.24374
	BATTERY	5502315	2, 30	2751158	15.567	0.00002
	CONDITION*BATTERY	38198	2, 30	19099	0.101	0.90420
LF POWER	CONDITION	1217454	1, 15	1217454	0.923	0.35182
	BATTERY	7701517	2, 30	3850759	3.018	0.06394
	CONDITION*BATTERY	854159	2, 30	427079	0.415	0.66435
VLF POWER	CONDITION	1035694	1, 15	1035694	0.999	0.33331
	BATTERY	18381844	2, 30	9190922	10.185	0.00042
	CONDITION*BATTERY	938307	2, 30	469154	0.585	0.56323
LF:HF	CONDITION	0.00975	1, 15	0.010	0.976	0.33887
	BATTERY	0.28394	2, 30	0.142	31.605	0.00000
	CONDITION*BATTERY	0.00381	2, 30	0.002	0.460	0.63555
LFn.u	CONDITION	0.00975	1, 15	0.010	0.976	0.33887
	BATTERY	0.28394	2, 30	0.142	31.605	0.00000
	CONDITION*BATTERY	0.00381	2, 30	0.002	0.460	0.63555
HFn.u	CONDITION	0.00975	1, 15	0.010	0.976	0.33887
	BATTERY	0.28394	2, 30	0.142	31.605	0.00000
	CONDITION*BATTERY	0.00381	2, 30	0.002	0.460	0.63555

The %LF (LF/HF) as well as the ratio between low- and high-frequency components increased ($p<0.05$) over time in both the *test* and *retest* sessions. Comparisons between *during* and *post-test* indicated no differences for the high-frequency, low-frequency, very low-frequency and the LF:HF ratio components, nor in the proportion of low-frequency to high-frequency power (%LF [LF/HF]).

Table LII: Battery-related changes in the frequency spectrum components measured during *test* and *retest* (all values are mean ± SD).

	TEST									**RETEST**								
	PRE			**DUR**			**POST**			**PRE**			**DUR**			**POST**		
	Mean	**SD**		**Mean**	**SD**		**Mean**	**SD**		**Mean**	**SD**		**Mean**	**SD**		**Mean**	**SD**	
HF Power (ms^2)	829	770	b c	311	195	a d	290	295	a d	927	538	b c f	497	455		394	423	d
LF Power (ms^2)	1626	1456		878	466		923	532		1652	1039		1050	663		1401	1814	
VLF Power (ms^2)	1531	965		760	711	d	736	679	d	1906	1698	b c f	1077	889		666	382	d
LF:HF	2.23	1.21	c f	3.56	1.89		4.64	2.85	a d e	2.25	1.96	c f	3.17	2.26	c	4.09	1.76	a d
% LF (LF/HF)	66.0	9.47	b c f	74.8	8.90	a d	78.2	10.1	a d	63.7	12.2	b c e f	71.5	9.87	d	77.9	8.55	a d

Different (p<0.05) to : ***a*** *= PRE 1 :* ***b*** *= DUR 1 :* ***c*** *= POST 1 :* ***d*** *= PRE 2 :* ***e*** *= DUR 2 :* ***f*** *= POST 2 : † = condition effect*

Small effects were demonstrated in the *retest* condition between *during* and *post-test* for high-frequency (*d* = 0.21), low-frequency (*d* = 0.47) and very low-frequency power (*d* = 0.30). In addition, moderate effects were observed for the normalised frequency data and ratio data in the *retest* condition (Table LIII). Noteworthy, the between-participant variability in frequency spectrum components is high, particularly *post-test*. This degree of variability was not evident in the time domain responses.

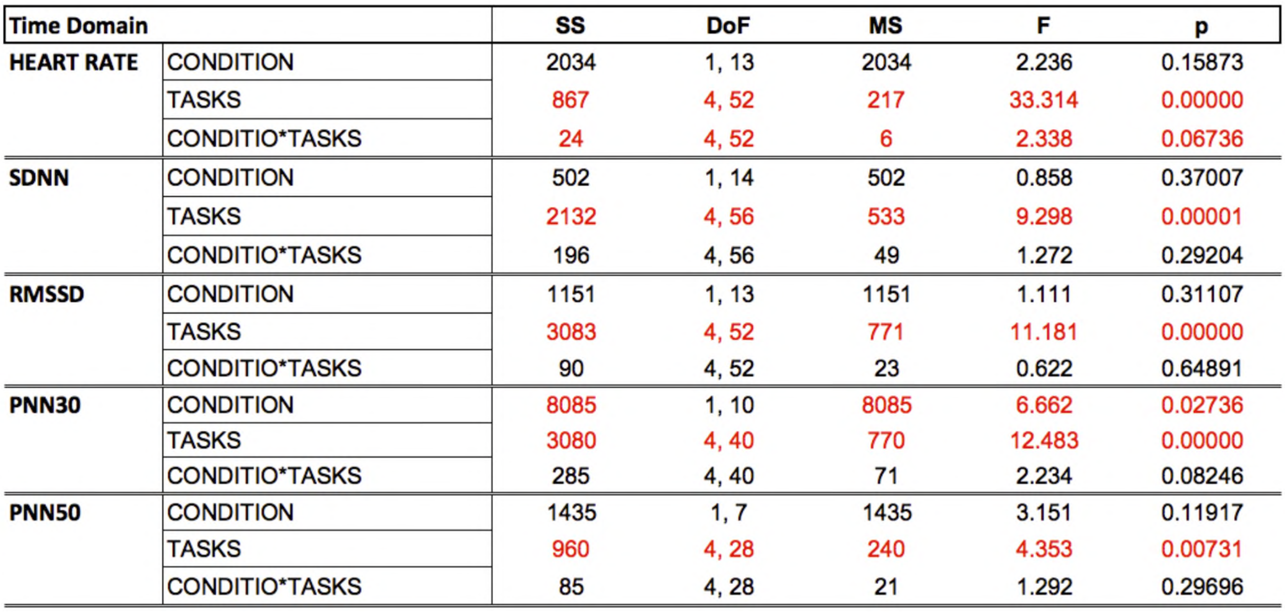
Table LIII: Frequency spectrum effect sizes (0.2-0.49 = small; 0.5-0.79 = moderate; >0.8 = large).

	PRE 1 vs. DUR 1	**PRE 1 vs. POST 1**	**DUR 1 vs. POST 1**	**PRE 2 vs. DUR 2**	**PRE 2. vs. POST 2**	**DUR 2 vs. POST 2**
HF Power	**0.92**	**0.92**	0.08	**0.86**	**1.07**	**0.21**
LF Power	**0.69**	**0.64**	0.09	**0.69**	**0.29**	**0.40**
VLF Power	**0.91**	**0.95**	0.03	**0.61**	**0.92**	**0.30**
LF:HF	**0.84**	**1.10**	**0.44**	**0.43**	**0.87**	**0.44**
LF % (n.u.)	**0.96**	**1.24**	**0.35**	**0.71**	**1.28**	**0.58**
HF % (n.u.)	**0.96**	**1.24**	**0.35**	**0.71**	**1.28**	**0.58**

5.6.3.2 Task-Related Differences

Within time domain measures a *condition effect* was observed for PNN30 (*p*<0.03) only, with *task effects* observed in all parameters (Table LIV). No *task effects* were found during *pre-test*, indicating that batting had a significant influence on heart rate parameters. One *interaction effect* of mean heart rate (condition*task) was observed. Task-related time domain changes in heart rate variability are presented in Table LV. Note: the table must be read in a vertical fashion to isolate effects to individual batteries.

Table LIV: Statistical interactions for heart rate parameters during cognitive assessment.



Time Domain		**SS**	**DoF**	**MS**	**F**	**p**
HEART RATE	CONDITION	2034	1, 13	2034	2.236	0.15873
	TASKS	867	4, 52	217	33.314	0.00000
	CONDITIO*TASKS	24	4, 52	6	2.338	0.06736
SDNN	CONDITION	502	1, 14	502	0.858	0.37007
	TASKS	2132	4, 56	533	9.298	0.00001
	CONDITIO*TASKS	196	4, 56	49	1.272	0.29204
RMSSD	CONDITION	1151	1, 13	1151	1.111	0.31107
	TASKS	3083	4, 52	771	11.181	0.00000
	CONDITIO*TASKS	90	4, 52	23	0.622	0.64891
PNN30	CONDITION	8085	1, 10	8085	6.662	0.02736
	TASKS	3080	4, 40	770	12.483	0.00000
	CONDITIO*TASKS	285	4, 40	71	2.234	0.08246
PNN50	CONDITION	1435	1, 7	1435	3.151	0.11917
	TASKS	960	4, 28	240	4.353	0.00731
	CONDITIO*TASKS	85	4, 28	21	1.292	0.29696

Heart rates were lower in the *retest* condition ($p > 0.05$). In both conditions, increasing time-on-task resulted in decreases ($p < 0.05$) in heart rate between tasks. Heart rates *during* and *post-test* in the *maze* task were higher ($p < 0.05$) than all subsequent tasks- a result consistent in both the *test* and *retest* conditions (Table LV). Additionally, within the *test* condition heart rates during the *detection* and *identification* tasks were higher ($p < 0.01$) than in the *one-back* task. These results indicate a steady decline in heart rate over time – *time-on-task effect*.

Changes in time domain measures are only evident between the first task in the battery (*maze*) and the last (*one-back*). RMSSD, SDNN and PNN30 increased significantly ($p < 0.05$) as cognitive assessment time progressed. Within the *test* condition, main effects are similar for SDNN and RMSSD, and are as follows: (i) after 15 and 30 overs, respectively, SDNN and RMSSD decreased ($p < 0.05$) between *maze* vs. *one-back* task, (ii) after 30 overs, RMSSD was significantly lower ($p < 0.05$) in the *maze* vs. *one card-learning* task, (iii) SDNN was also significantly lower ($p < 0.05$) after 30 overs in the *detection* task compared to the *one-back* and *in the identification* vs. *one-back* task. Furthermore, the variability in PNN30 during assessment 2 (*during*) was substantially lower in the *maze* task compared to the *one card-learning* tasks (*p*<0.04) and *one-back* tasks (*p*<0.01). *Post-test* PNN30 was lowest in the *maze* when compared to the *one-back* task (*p*<0.01). During *retest*, RMSSD and SDNN demonstrated no main effects after 15 overs of batting. *Post-test*, RMSSD and SDNN in the *maze* task *were* lower than the *one card-learning* (*p*<0.01) and *one-back* (*p*<0.01) tasks. In the second assessment (*during*), PNN30 was also different (*p*<0.01) between the *maze* and *identification* tasks, whereas *post-test*, additional differences included; *maze* vs. *identification* (*p*<0.01) and *maze* vs. *one card-learning* tasks (*p*<0.01). Collectively, the PNN results show that the total variability in heart rate increases over time. A *condition effect* of PNN30 was also observed, where responses were higher in during *retest* (*p*<0.03).

Table LV: Task-related differences in time domain parameters measured during *test* and *retest*. Tasks presented in order of completion (all values are mean ± SD).

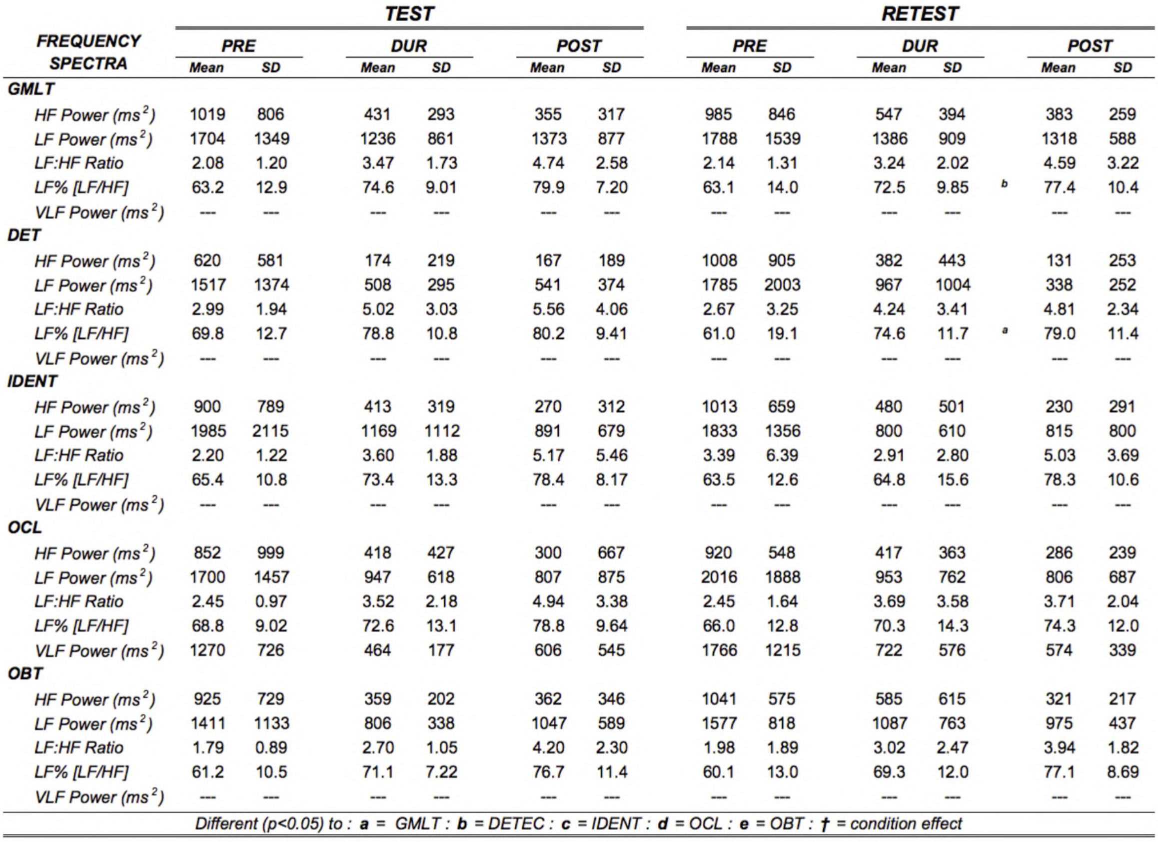
TIME DOMAIN	TEST								RETEST							
	PRE		DUR			POST			PRE		DUR			POST		
	Mean	SD	Mean	SD		Mean	SD		Mean	SD	Mean	SD		Mean	SD	
GMLT																
HR	74	8.98	92	11.0	b c d e	98	10.0	b c d e	70	8.47	86	13.3	b c d e	96	12.5	b c d e
SDNN (ms)	30.2	12.7	16.6	7.91	e	16.6	7.40	e	38.1	15.7	21.9	14.6		13.1	6.40	d e
rMSSD (ms)	38.1	16.2	20.8	9.77	e	27.6	33.3	d e	47.6	19.8	28.1	19.5		16.5	8.26	d e
PNN30 %	39.0	19.2	15.2	16.8	d e	8.72	11.2	e	48.6	18.1	27.7	19.0	c d e	8.68	9.79	c d e †
PNN50 %	21.2	16.4	7.27	11.6	e	3.65	5.55		33.4	13.0	13.9	17.0	d e	2.80	4.55	d e
DET																
HR	72	8.47	88	9.92	a e	89	21.9	a d e	70	8.66	83	12.3	a	93	12.4	a d e
SDNN (ms)	35.0	13.8	22.4	7.54		18.3	7.56	e	37.3	9.83	23.7	11.1		18.6	8.87	
rMSSD (ms)	44.2	17.8	28.8	10.1		23.0	9.66		47.1	12.5	30.3	14.5		23.8	11.9	
PNN30 %	42.0	16.4	21.9	12.6		11.6	7.00		48.6	16.6	29.3	20.5		16.1	11.7	e †
PNN50 %	24.5	14.7	8.68	7.28		3.65	2.91		30.3	14.2	17.0	14.0		6.20	5.35	
IDENT																
HR	74	9.52	88	9.70	a e	89	20.7	a d e	70	8.39	81	11.5	a	92	12.8	a e
SDNN (ms)	33.8	16.3	22.5	6.71		18.2	8.04	e	37.2	12.4	24.9	10.7		20.0	8.33	
rMSSD (ms)	42.6	21.4	28.3	8.51		23.3	11.7		46.9	15.6	31.7	13.7		25.6	11.1	
PNN30 %	38.5	18.4	19.9	14.0		11.3	8.98		50.8	16.4	31.7	18.5	a	19.4	15.4	a †
PNN50 %	22.5	15.7	7.42	7.35		4.33	4.27		31.1	14.4	16.6	12.7		9.05	9.27	
OCL																
HR	73	9.41	87	8.99	a	86	24.4	a b c	70	8.95	81	11.5	a	90	12.3	a b
SDNN (ms)	34.5	13.0	22.4	6.95		20.3	8.87		38.0	10.8	26.9	12.4		22.3	7.67	a
rMSSD (ms)	43.7	17.1	28.4	8.69		27.8	9.75	a	47.7	13.8	34.2	15.9		28.3	10.1	a
PNN30 %	43.3	17.5	22.3	13.0	a	14.8	9.03		49.1	14.9	32.7	18.3	a	19.6	15.5	a †
PNN50 %	25.4	17.4	8.99	6.56		5.50	4.47		31.6	14.1	17.3	14.7	a	9.23	9.66	a
OBT																
HR	73	8.92	85	8.74	a b c	90	8.75	a b c	71	9.81	80	11.53	a	88	13.0	a b c
SDNN (ms)	36.4	14.0	25.3	9.64	a	26.3	17.6	a b c	37.1	12.5	27.3	10.3		24.0	9.28	a
rMSSD (ms)	45.9	17.7	32.2	12.1	a	28.5	10.7	a	46.7	15.6	35.0	13.4		30.4	11.6	a
PNN30 %	43.7	16.3	28.1	13.7	a	18.6	9.22	a	46.9	16.5	33.3	17.8	a	23.1	16.4	a b †
PNN50 %	26.6	15.4	12.2	9.00	a	7.34	5.39		28.5	15.7	16.7	14.0	a	10.9	13.0	a

*Different (p<0.05) to : **a** = GMLT : **b** = DETEC : **c** = IDENT : **d** = OCL : **e** = OBT : **†** = condition effect*

Table LVI: Statistical interactions for frequency spectra during cognitive assessment.

Frequency Spectra		SS	DoF	MS	F	p
HF POWER	CONDITION	667817	1, 13	667817	0.525	0.48151
	TASKS	2184303	4, 52	546076	4.534	0.00323
	CONDITIO*TASKS	334246	4, 52	83561	0.742	0.56746
LF POWER	CONDITION	189840	1, 13	189840	0.065	0.80336
	TASKS	13743449	4, 52	3435862	4.568	0.00309
	CONDITIO*TASKS	1446085	4, 52	361521	0.713	0.58702
LF% [LF/HF]	CONDITION	1096	1, 13	1096	1.849	0.19701
	TASKS	1149	4, 52	287	3.219	0.01955
	CONDITIO*TASKS	306	4, 52	76	1.389	0.25078
LF:HF	CONDITION	7	1, 13	7	0.180	0.67793
	TASKS	74	4, 52	18	3.867	0.00798
	CONDITIO*TASKS	9	4, 52	2	0.733	0.57332

Table LVII: Task-related changes in frequency spectra during *test* and *retest*. Tasks presented in order of completion (all values are mean ± SD).



FREQUENCY SPECTRA	**TEST**						**RETEST**						
	PRE		**DUR**		**POST**		**PRE**		**DUR**			**POST**	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**		**Mean**	**SD**
GMLT													
HF Power (ms^2)	1019	806	431	293	355	317	985	846	547	394		383	259
LF Power (ms^2)	1704	1349	1236	861	1373	877	1788	1539	1386	909		1318	588
LF:HF Ratio	2.08	1.20	3.47	1.73	4.74	2.58	2.14	1.31	3.24	2.02		4.59	3.22
LF% [LF/HF]	63.2	12.9	74.6	9.01	79.9	7.20	63.1	14.0	72.5	9.85	b	77.4	10.4
VLF Power (ms^2)	---	---	---	---	---	---	---	---	---	---		---	---
DET													
HF Power (ms^2)	620	581	174	219	167	189	1008	905	382	443		131	253
LF Power (ms^2)	1517	1374	508	295	541	374	1785	2003	967	1004		338	252
LF:HF Ratio	2.99	1.94	5.02	3.03	5.56	4.06	2.67	3.25	4.24	3.41		4.81	2.34
LF% [LF/HF]	69.8	12.7	78.8	10.8	80.2	9.41	61.0	19.1	74.6	11.7	a	79.0	11.4
VLF Power (ms^2)	---	---	---	---	---	---	---	---	---	---		---	---
IDENT													
HF Power (ms^2)	900	789	413	319	270	312	1013	659	480	501		230	291
LF Power (ms^2)	1985	2115	1169	1112	891	679	1833	1356	800	610		815	800
LF:HF Ratio	2.20	1.22	3.60	1.88	5.17	5.46	3.39	6.39	2.91	2.80		5.03	3.69
LF% [LF/HF]	65.4	10.8	73.4	13.3	78.4	8.17	63.5	12.6	64.8	15.6		78.3	10.6
VLF Power (ms^2)	---	---	---	---	---	---	---	---	---	---		---	---
OCL													
HF Power (ms^2)	852	999	418	427	300	667	920	548	417	363		286	239
LF Power (ms^2)	1700	1457	947	618	807	875	2016	1888	953	762		806	687
LF:HF Ratio	2.45	0.97	3.52	2.18	4.94	3.38	2.45	1.64	3.69	3.58		3.71	2.04
LF% [LF/HF]	68.8	9.02	72.6	13.1	78.8	9.64	66.0	12.8	70.3	14.3		74.3	12.0
VLF Power (ms^2)	1270	726	464	177	606	545	1766	1215	722	576		574	339
OBT													
HF Power (ms^2)	925	729	359	202	362	346	1041	575	585	615		321	217
LF Power (ms^2)	1411	1133	806	338	1047	589	1577	818	1087	763		975	437
LF:HF Ratio	1.79	0.89	2.70	1.05	4.20	2.30	1.98	1.89	3.02	2.47		3.94	1.82
LF% [LF/HF]	61.2	10.5	71.1	7.22	76.7	11.4	60.1	13.0	69.3	12.0		77.1	8.69
VLF Power (ms^2)	---	---	---	---	---	---	---	---	---	---		---	---

*Different ($p<0.05$) to : **a** = GMLT : **b** = DETEC : **c** = IDENT : **d** = OCL : **e** = OBT : † = condition effect*

Frequency spectra showed one *task effect*, where the relative percentage of low-frequency power (LF% [LF/HF]) was higher (p<0.03) in the *detection* task (compared to the maze task) during the second assessment of the *retest* condition (Table LVII). The results here are similar to that of *phase 1*, where the frequency spectra decrease as time-on-task increases.

In summary, prolonged batting increased heart rate and decreased heart rate variability. However, as task duration increased, a reduction and stabilisation of heart rate was observed with a concurrent increase in heart rate variability. Batters therefore, increased the effort invested between batteries (*battery effect*); however, the ability to regulate effort decreased as the task battery duration increased (*time-on-task effect*).

5.7 Summary

Briefly, repeated shuttle running imposed high physiological loads, which resulted in slower sprint times and a negligible improvement in vertical jump height. The increased physiological load imposed by prolonged batting with repeated shuttle running, resulted in elevated physiological responses during cognitive assessments. As cognitive test time increased, time domain measures increased while frequency spectra responses were mixed. Prolonged batting negatively impacted executive function, psychomotor function and vigilance in the *test* session; however, results did not attain statistical significance.

During *retest* the physiological responses imposed by BATEX were similar to those in the test session, however, the magnitude of changes was less in the *retest* session. The physical performance of batters in this session was reduced to a lesser extent than that in the *test* session, and for vertical jump, *post-test* responses were better than the *pre-test* measures. Heart rate variability showed similar trends to the *test* session, however, the magnitude of these changes were again smaller. In comparison to *test*, executive function, psychomotor function and vigilance were improved, while visual learning and memory (long-term and short-term working memory) were worse in this session.

The *test-retest* reliability was good and *condition effects* were minimal. No *condition effects* were observed in any of the performance data. Rather only physiological data demonstrated *condition effects*. This suggests that the cardiovascular load of the *retest* session was lower than in the *test* session.

Table LVIII: Summary of primary findings. Arrows indicate the direction of the change in performance while colours indicate the effect of the result (red = reduced performance, green = improved performance, blue = negligible change).

		TEST						***RETEST***						***TEST vs. RETEST***			
		PRE vs. POST			***DUR vs. POST***			***PRE vs. POST***			***DUR vs. POST***						
		△	***P value***	***Cohens d***	△	***P value***	***Cohens d***	△	***P value***	***Cohens d***	△	***P value***	***Cohens d***	△		***P value***	***Cohens d***
BATTING PERFORMANCE	*Sprint Times*	↑	< 0.01	0.70	↑	> 0.05	0.43	↑	< 0.01	0.39	↑	> 0.05	0.12	Retest	↓	> 0.05	0.49
	Vertical Jump - CMJ	↑	> 0.05	0.01				↑	> 0.05	0.05				Retest	↑	> 0.05	0.43
	Vertical Jump - SJ	↓	> 0.05	0.05				↑	> 0.05	0.08				Retest	↑	> 0.05	0.40
PHYSIOLOGICAL PERFORMANCE	*Heart Rate*	↑	< 0.01	0.93	↑	> 0.05	0.74	↑	< 0.01	0.61	↑	> 0.05	0.62	Retest	↓	< 0.04	0.39
	Mass - Fluid Balance	↓	< 0.01	0.07				↓	< 0.01	0.42				Retest	↓	< 0.03	0.09
PERCEPTUAL RESPONSES	*RPE: Central*	↑	< 0.01	1.91	↑	> 0.05	1.10	↑	< 0.01	2.24	↑	> 0.05	1.24	Retest	↓	> 0.05	0.08
	RPE: Local	↑	< 0.01	2.19	↑	> 0.05	1.30	↑	< 0.01	2.81	↑	> 0.05	1.65	Retest	↓	> 0.05	0.05
COGNITIVE PERFORMANCE	*Heart Rate - Battery*	↑	< 0.01	2.22	↑	< 0.02	0.61	↑	< 0.01	2.11	↑	< 0.01	0.97	Retest	↓	> 0.05	0.32
	Heart Rate - Task	↓	< 0.01	-				↓	< 0.01					Retest	↓	-	-
	HRV: SDNN - Battery	↓	< 0.01	1.42	↓	> 0.05	0.24	↓	< 0.01	1.56	↓	> 0.05	0.39	Retest	↑	> 0.05	0.20
	HRV: SDNN - Task	↑	< 0.01	-				↑	< 0.01					Retest	↑	-	-
	HRV: rMSSD - Battery	↓	< 0.01	1.23	↓	> 0.05	0.12	↓	< 0.01	1.44	↓	> 0.05	0.36	Retest	↑	> 0.05	0.12
	HRV: rMSSD - Task	↑	< 0.01	-				↑	< 0.01					Retest	↑	-	-
	HRV: HF Power	↓	< 0.02	0.92	↓	> 0.05	0.08	↓	< 0.01	1.07	↓	> 0.05	0.21	Retest	↑	> 0.05	0.27
	HRV: LF Power	↓	> 0.05	0.64	↑	> 0.05	0.09	↓	> 0.05	0.29	↑	> 0.05	0.40	Retest	↑	> 0.05	0.80
	HRV: HF:LF Ratio	↑	< 0.01	1.24	↑	> 0.05	0.35	↑	< 0.01	1.28	↑	> 0.05	0.58	Retest	↓	> 0.05	0.03
	HRV: $HF_{n.u.}$	↓	< 0.01	1.24	↓	> 0.05	0.35	↓	< 0.01	1.28	↓	> 0.05	0.58	Retest	-	> 0.05	0.03
	HRV: $LF_{n.u.}$	↑	< 0.01	1.24	↑	> 0.05	0.35	↑	< 0.01	1.28	↑	> 0.05	0.58	Retest	-	> 0.05	0.03
	Executive Function	↓	> 0.05	0.02	↓	> 0.05	0.14	↑	> 0.05	0.16	↓	> 0.05	0.50	Retest	↑	> 0.05	0.59
	Psychomotor Function	↓	> 0.05	0.02	-	> 0.05	0.01	↑	> 0.05	0.27	↑	> 0.05	0.27	Retest	↑	> 0.05	0.12
	Vigilance	↓	> 0.05	0.04	-	> 0.05	0.05	↑	> 0.05	0.32	↑	> 0.05	0.31	Retest	↑	> 0.05	0.14
	Visual Learning & Memory	↑	> 0.05	0.17	↓	> 0.05	0.06	-	> 0.05	0.04	↓	> 0.05	0.24	Retest	↓	> 0.05	0.03
	Attention & Working Memory	↑	> 0.05	0.10	↑	> 0.05	0.21	↓	> 0.05	0.10	↑	> 0.05	0.15	Retest	↓	> 0.05	0.23

CHAPTER VI - RESULTS: SCHOOLBOY VS. ACADEMY BATTERS

These subsequent results will contrast differences in responses between samples, but due to the distinct methodological differences, statistical analyses were not completed and are therefore, not presented. A two tailed independent t-test compared sample characteristics and was the only instance where statistical analysis was computed. The most obvious differences between samples were age ($p<0.01$) and playing experience ($p<0.01$).

Table LIX: Demographic and anthropometric sample comparison (all values are mean ± SD). Schoolboy $n= 15$; academy $n=16$; * denotes significant difference ($p<0.05$).

	AGE	***RHR***	***STATURE***	***MASS***	***BMI***	***BODY FAT***	***EXPERIENCE***
	years	bt.min^{-1}	m	kg	kg/m^{2}	%	years
Schoolboy	17.7 ± 1.0	65 ± 10	1.75 ± 0.1	76.5 ± 11.3	25.0 ± 2.7	8.43 ± 4.6	4.10 ± 1.0
Academy	19.1 ± 1.0	70 ± 8	1.76 ± 0.1	75.0 ± 8.4	24.3 ± 2.0	9.27 ± 3.2	5.81 ± 1.4
P-value	< 0.01*	0.18	0.56	0.77	0.41	0.57	< 0.01*

6.1 Physiological Responses

In most stages, BATEX induced higher exercising heart rates in schoolboy batters when compared to academy batters. When expressed in relative terms (%HR$_{max}$), the physiological load of schoolboys was higher in most stages. In addition, the inter-individual variability of schoolboy batters was higher in all stages when compared to academy batters, particularly in the closing stages.

Table LX: Phase comparison of mean (±SD) heart rate responses.

	STAGE 1		***STAGE 2***		***STAGE 3***		***STAGE 4***		***STAGE 5***		***STAGE 6***	
	% HR$_{MAX}$	**SD**	**% HR$_{MAX}$**	**SD**	**% HR$_{MAX}$**	**SD**	**% HR$_{MAX}$**	**SD**	**% HR$_{MAX}$**	**SD**	**% HR$_{MAX}$**	**SD**
Schoolboy	60.8	9.68	69.4	10.6	64.0	8.80	72.9	10.1	71.5	10.2	77.4	10.1
Academy Test	63.0	7.56	69.6	8.19	64.3	8.55	71.0	8.67	71.7	7.99	76.9	7.11
Academy Retest	59.4	7.88	68.0	8.82	60.0	9.18	68.5	8.88	65.6	10.9	73.6	7.99
Mean ± SD	61 ± 8		69 ± 9		63 ± 9		71 ± 9		70 ± 10		76 ± 8	

Schoolboy batters lost more body mass and had a higher percentage sweat loss during BATEX. Despite shorter total protocol duration, academy batters had higher rates of sweat loss in both sessions (Table LXI).

Table LXI: A comparison of body mass loss and changes in fluid loss between phases.

PERFORMANCE △	**Body Mass**		**Sweat Loss**	**Sweat Rate**
	kg	**%**	**Relative (% BM)**	**Relative ($L.h^{-1}$)**
Schoolboy	0.97	1.27	1.36	0.34
Academy Test	0.58	0.75	1.32	0.36
Academy Retest	0.67	0.87	1.33	0.36
Mean	**0.74**	**0.96**	**1.33**	**0.35**

6.2 Sprint times

With the exception of stage 2, academy batters had faster sprint times in all stages. Additionally, academy batters were faster across all run denominations, with the exception of singles, where schoolboy batters attained faster times. Comparatively, deterioration in mean sprint times between stage 2 and 6 was larger in the schoolboy sample. The sprint time decrement was smaller for academy batters in the *retest* session.

Table LXII: Sprint time comparison of maximal intensity stages.

	Sprint Times (ms)			
	STAGE 2	***STAGE 4***	***STAGE 6***	**△ 2 vs 6**
Schoolboy	2.255	2.297	2.363	-0.108
Academy Test	2.257	2.290	2.351	-0.095
Academy Retest	2.227	2.268	2.293	-0.066
Mean	**2.246**	**2.285**	**2.336**	**-0.090**

6.3 Perceptual Responses

The trends for perceived exertion were the same for schoolboy and academy batters. Both samples perceived the maximal-intensity stages to elicit higher cardiovascular and muscular demand (with stage 6 rated higher $p<0.05$ than stage 2 and 4). Both schoolboy and academy batters rated central RPE consistently higher than local RPE, with main effects ($p<0.05$) observed in schoolboy batters in stage 4 and 6. In both the *test* and *retest* sessions, academy batters rated cardiovascular demand higher than muscular demand in stage 2 only.

Table LXIII: Pearson correlation analysis between central ratings of perceived exertion and heart rate.

Pearson (r)	STAGE 1	STAGE 2	STAGE 3	STAGE 4	STAGE 5	STAGE 6
Schoolboy	0.22	0.18	0.22	0.19	0.41	0.39
Academy Test	0.28	0.13	0.19	0.22	0.48	0.47
Academy Retest	0.20	0.09	0.20	0.41	0.45	0.60
Mean	**0.23**	**0.13**	**0.20**	**0.28**	**0.45**	**0.49**

The increase in correlation strength between stage one and six demonstrate that both samples accurately perceived the increase in heart rate over time (Table LXIII). Furthermore, these correlations show that batters were more accurate at rating later stages of the protocol.

Table LXIV: Stage and intensity comparisons of the rate of Increase in RPE over time.

	OVERS 1-5		OVERS 1-15		OVERS 16-30		OVERS 26-30	
% Increase	Central	Local	Central	Local	Central	Local	Central	Local
Schoolboy	12%	11%	40%	34%	42%	40%	12%	11%
Academy Test	14%	12%	33%	37%	42%	39%	9%	10%
Academy Retest	14%	10%	52%	46%	45%	45%	9%	14%
Mean	13%	11%	42%	39%	43%	41%	10%	11%

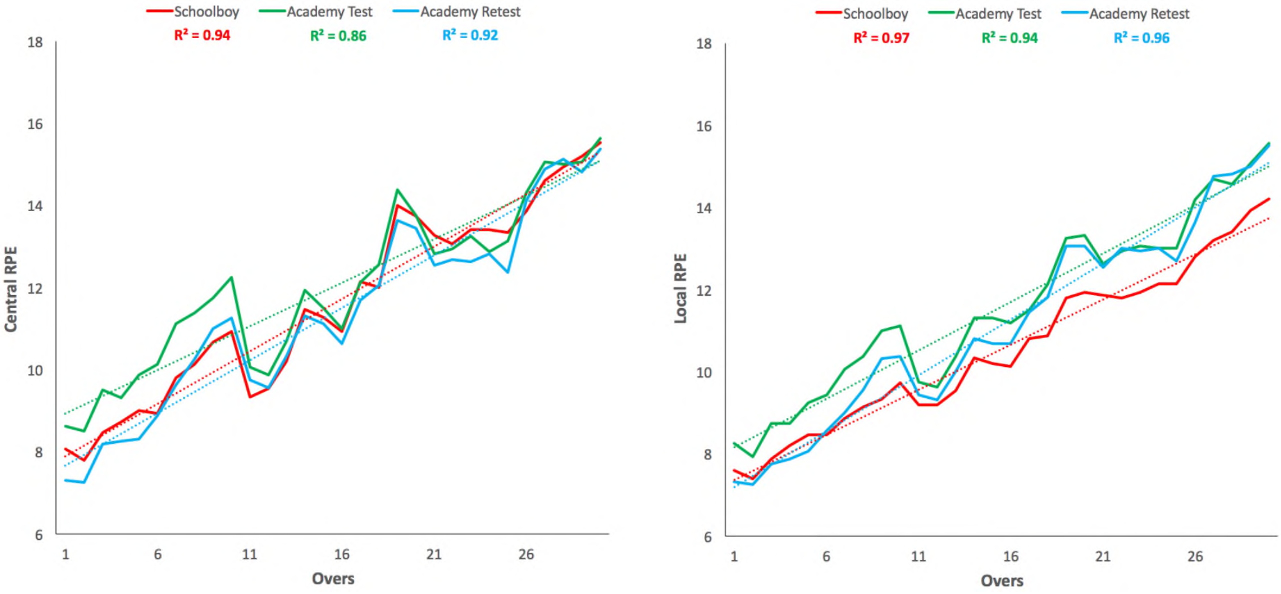


Figure 22: Rate of increase in central and local ratings of perceived exertion (overs 6-10, 16-21 and 26-30 = maximal intensity stages).

While Figure 22 depicts RPE as data that was recorded continuously, this was not the case. However, this was the best means of graphically displaying the data, so that the trends in perceived exertion could be shown between samples. Schoolboy batters perceived BATEX to induce higher cardiovascular and muscular demand than academy batters. Schoolboy batters also had higher rates of increase in RPE for the first 15 and last 15 overs (Table LXIV). In the first 10 overs, the perception of effort and rate of increase in effort was higher in academy batters.

6.4 Visual Attention/ Vigilance

While accuracy rates were similar between samples, the response times of schoolboy batters in the *identification* task were faster than those produced by academy batters. In spite of this, absolute responses suggest a larger decrement in visual attention for schoolboy batters (*d* = 0.56) compared to academy batters (*d* = 0.04). After the first 15 overs (*pre* vs. *during*), schoolboy batters showed larger decrements (*d* = 0.16) in response times than academy batters (*d*= 0.02). Similarly, when comparing the last 15 overs of batting (*during* vs. *post*), schoolboy batters response time showed a small impairment (*d* =0.37) while academy batters processing speed was maintained (*d* =0.05). However, the slower mean processing speeds of academy batters, when combined with accuracy rates that are comparable to schoolboy batters, produces a higher inverse efficiency score (Table LXV). This indicates better overall performance in schoolboy batters between *pre* and *post-test*.

Table LXV: Performance changes in response time (ms) and accuracy rates (%) as measured by the *identification* task. Negative values indicate performance decrement.

	PRE vs. DUR		***DUR vs. POST***		***PRE vs. POST***		
PERFORMANCE △	***ms***	***ACC***	***ms***	***ACC***	***ms***	***ACC***	***IES***
Schoolboy	-12.1	-2%	-32.8	1%	-44.9	0%	531
Academy Test	-11.9	1%	10.2	-1%	-1.65	1%	558
Academy Retest	14.2	1%	47.2	0%	61.4	1%	535

6.5 Psychomotor function

Schoolboy batters had faster mean response times in all test batteries when compared to academy batters. The decrements over time for schoolboy and academy batters were *d* =

0.37 and 0.02, respectively – indicating a greater effect of prolonged batting on the younger sample. Despite schoolboy batters incurring a greater decrement in response time between *pre* and *post-test*, the inverse efficiency score shows that performance was better than academy batters (Table LXVI). While academy batters had improvements in psychomotor function after the first 15 overs, the psychomotor function of both samples was impaired in the last 15 overs. However, the decrement experienced by academy batters in the final 15 overs was larger than that of the school boys. The higher inverse efficiency score in academy batters is most likely the result of the larger decrement in speed in the final 15 overs and the slower mean response times. The best inverse efficiency score was attained in the *retest* session of academy batters. The improved visual attention in the *retest* academy session suggests that a learning effect could be present in the *retest* session.

Table LXVI: Performance changes in response time (ms) and accuracy rates (%) in the *detection* task. Negative values indicate performance decrement.

	PRE vs. DUR		DUR vs. POST		PRE vs. POST		
PERFORMANCE △	**ms**	**ACC**	**ms**	**ACC**	**ms**	**ACC**	**IES**
Schoolboy	-6.74	-2%	-5.83	2%	-12.6	0%	317
Academy Test	19.1	1%	-19.9	0%	-0.84	0%	325
Academy Retest	-53.1	0%	70.1	0%	17.0	0%	291

6.6 Memory

6.6.1 Working Memory

Table LXVII: Performance changes in response time (ms) and accuracy rates (%) during the *one-back* task.

	PRE vs. DUR		DUR vs. POST		PRE vs. POST		
PERFORMANCE △	**ms**	**ACC**	**ms**	**ACC**	**ms**	**ACC**	**IES**
Schoolboy	0.68	-3%	-31.7	-2%	-31.0	-5%	760
Academy Test	24.9	-2%	16.8	2%	41.7	0%	751
Academy Retest	-1.50	1%	44.0	0%	42.5	1%	767

Schoolboy batters demonstrated a moderate impairment in working memory over time (d =0.61). This decrement was not matched by academy batters who experienced improved accuracy (d = 0.10) of working memory *post-test*. While schoolboy batters performed the task faster than academy batters, this speed appears to be detrimental to response accuracy. Table LXVII shows that both samples' response accuracy decreases in the first 15 overs, with a larger decrement found in schoolboy batters (*d* = 0.54) versus academy batters (*d* = 0.13). With an increase in batting intensity (final 15 overs), only schoolboy batters experience further decrement. Therefore, academy batters are better able to maintain performance over time. This is the first task that does not show a learning effect between *test* and *retest* in the academy batters, where the inverse efficiency score shows reduced performance in the *retest* session.

6.6.2 Visual Learning and Memory

Visual learning and memory were unchanged in schoolboy (*d* =0.01) and academy batters (*d* =0.17) over time (Table LXVIII). At all assessment points, academy batters attained higher accuracy rates, while school boy batters were faster in response to the stimuli in each test battery. The initial 15 overs had facilitative effects in both samples, whereas high-intensity batting had detrimental effects on response accuracy in both samples. The lower efficiency score of schoolboy batters indicates better performance over time, however this is again attributable to faster processing speeds.

Table LXVIII: Response time (ms) and accuracy rate (%) changes in visual learning and memory.

	PRE vs. DUR		**DUR vs. POST**		**PRE vs. POST**		
PERFORMANCE △	***ms***	***ACC***	***ms***	***ACC***	***ms***	***ACC***	***IES***
Schoolboy	8.32	2%	44.2	-2%	52.6	0%	1229
Academy Test	18.3	3%	70.5	-1%	88.8	2%	1286
Academy Retest	19.4	1%	30.4	0%	49.8	1%	1197

6.7 Executive Functions

While both schoolboy and academy batters improved movement times significantly ($p<0.05$; $d = 0.93$ and $p<0.05$; $d = 0.80$) in the *maze* task, error rates were highest *post-test* in both samples (Table LXIX). The decrement in executive function over time was larger in schoolboy batters (*d* = 0.58) while error rates of academy batters increased by a negligible margin (*d* = 0.02). The academy batters improved response accuracy after 15 overs of batting, reducing the number of errors by 0.88. Following high-intensity batting, error rates of schoolboy and academy batters increased (*d* = 0.14 and 0.18, respectively). The efficiency score was similar between samples, with schoolboys demonstrating improved performance in the maze task.

Table LXIX: Changes in error rates and movement speed during the Maze task.

	PRE vs. DUR		DUR vs. POST		PRE vs. POST		
PERFORMANCE △	**mvs.s^{-1}**	**ERR**	**mvs.s^{-1}**	**ERR**	**mvs.s^{-1}**	**ERR**	**IES**
Schoolboy	0.14	3.93	0.07	3.60	0.21	7.53	1.80
Academy Test	0.06	-0.88	0.08	1.50	0.14	0.63	1.84
Academy Retest	0.00	2.56	0.13	-5.44	0.13	-2.88	2.17

The contribution of rule-break and perseverative errors show that both samples had a higher frequency of decision making errors in the final 15 overs of the simulation. Schoolboy batters made the greatest number of rule-break and perseverative errors over time suggesting that BATEX affected schoolboys to a greater extent than academy batters. In the academy *retest* session, total error rates and perseverative errors were reduced, while rule-break errors increased. This mixed result suggests that task performance improved, but academy batters were more prone to errors of decision making.

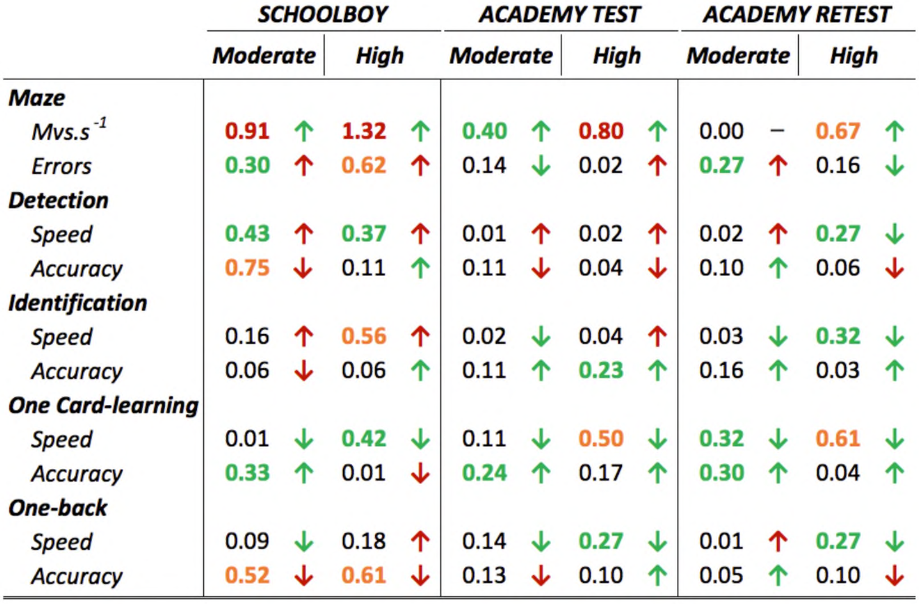
Table LXX: Changes decision-making (rule-break) errors and response inhibition (perseverative) errors between samples and batteries.

	RULE-BREAK ERRORS			PERSEVERATIVE ERRORS		
PERFORMANCE △	**PRE vs. DUR**	**DUR vs. POST**	**PRE vs. POST**	**PRE vs. DUR**	**DUR vs. POST**	**PRE vs. POST**
Schoolboy	3.07	1.40	4.47	0.33	0.13	0.47
Academy Test	-1.44	1.00	-0.44	-0.06	0.25	0.19
Academy Retest	1.44	-0.50	0.94	-0.13	0.00	-0.13

6.8 Summary

BATEX imposed higher cardiovascular loads in schoolboy batters with greater sprint time decrements in this sample. The physiological and muscular load demanded was accurately perceived in both samples, with schoolboy batters rating perceived effort. Schoolboy batters experienced larger time-related decrements in cognitive performance, while academy batters showed few cognitive decrements (Table LXXI).

Table LXXI: Effect size sample comparisons for intensity-dependent cognitive performance. Numbers are effect sizes (red: large effect, orange: moderate effect, green: small effect) and arrows are direction of change (green: performance improvement, red: performance impairment).



	SCHOOLBOY		ACADEMY TEST		ACADEMY RETEST	
	Moderate	High	Moderate	High	Moderate	High
Maze						
Mvs.s^{-1}	0.91 ↑	1.32 ↑	0.40 ↑	0.80 ↑	0.00 –	0.67 ↑
Errors	0.30 ↑	0.62 ↑	0.14 ↓	0.02 ↑	0.27 ↑	0.16 ↓
Detection						
Speed	0.43 ↑	0.37 ↑	0.01 ↑	0.02 ↑	0.02 ↑	0.27 ↓
Accuracy	0.75 ↓	0.11 ↑	0.11 ↓	0.04 ↓	0.10 ↑	0.06 ↓
Identification						
Speed	0.16 ↑	0.56 ↑	0.02 ↓	0.04 ↑	0.03 ↓	0.32 ↓
Accuracy	0.06 ↓	0.06 ↑	0.11 ↑	0.23 ↑	0.16 ↑	0.03 ↑
One Card-learning						
Speed	0.01 ↓	0.42 ↓	0.11 ↓	0.50 ↓	0.32 ↓	0.61 ↓
Accuracy	0.33 ↑	0.01 ↓	0.24 ↑	0.17 ↑	0.30 ↑	0.04 ↑
One-back						
Speed	0.09 ↓	0.18 ↑	0.14 ↓	0.27 ↓	0.01 ↑	0.27 ↓
Accuracy	0.52 ↓	0.61 ↓	0.13 ↓	0.10 ↑	0.05 ↑	0.10 ↓

In schoolboy batters, both moderate- and high-intensity batting impaired performance in all primary outcome variables. The magnitude of effect was greater *post-test*. In academy batters, moderate-intensity batting facilitated performance in all outcome variables, but the magnitude of these effects were negligible (d<0.2). Following high-intensity batting, the facilitative effects accrued from moderate intensity batting were annulled, but performance was not impaired (d<0.2). During the academy *retest* session, similar trends were observed after moderate-intensity batting, but the *maze* task showed a small impairment. *Post-test* performance in this session was improved in all tasks except the working memory task.

CHAPTER VII - DISCUSSION

The current investigation was designed to explore the impact of prolonged (30 overs) batting on cognitive, physiological and physical responses. Performed in a three-study design, this investigation aimed to determine which cognitive domains and to what extent these were affected by prolonged batting. Further, the study aimed to contribute to the existing literature on the physiological and muscular responses of batting. It was hypothesised that the prolonged and intermittent nature of the simulation would induce cardiovascular strain and muscular fatigue in batters and that, over time, cognitive performance would deteriorate.

In a cohort of schoolboy cricketers (17.7 ± 0.96 years) BATEX resulted in a slowing of sprint times ($p<0.01$; $d = 0.84$) and elevated physiological responses ($p<0.01$; $d = 1.85$). Prolonged batting impaired executive functions ($p<0.04$; $d = 0.85$) with effect sizes suggesting that attention and working memory ($d = 0.61$) and vigilance ($d = 0.56$) were moderately impaired. In an academy cohort, the statistical trends were similar for physiological responses ($p<0.01$; $d = 0.70$) and sprint times ($p<0.01$; $d = 1.88$), however, cognitive performance was not impaired ($p>0.05$; $d < 0.50$). This suggests that the cognitive abilities of academy batters are unaffected by prolonged batting. Importantly, the reliability of all results obtained in *phase 2* (*test*) were affirmed in the *retest* phase of data collection.

Before the distinction between the samples can be discussed, it is important to make the following notes: research indicates that the most notable physiological adaptations of improved training status are lower resting heart rate, lower exercising heart rate and improved recovery rates (Baechle & Earle, 2008; Daanen, Lamberts, Kallen, Jin, & Van Meeteren, 2012). Therefore lower resting heart rate would suggest that schoolboy batters had better resting cardiovascular efficiency, however, the lower exercising heart rates of academy batters and the faster heart rate recovery rates between overs and stages, suggest that these batters were of higher training status. Further evidence in this regard is provided in section 7.4. Secondly, the methodological differences between *phase 1* and *phase 2* and *3* do not allow statistical comparisons. Therefore any comparisons made between schoolboy and academy batters are purely for the purpose of discussion and not to infer differences between samples. Where comparison can be made is on anthropometric and baseline heart rate data, where an independent t-test was computed.

7.1 Cognitive Responses

Null hypothesis testing failed to reveal changes ($p<0.05$) in cognitive performance between *pre* and *post-test*, however, a number of significant differences ($p<0.05$) were observed between *during* and *post*. Additionally, Cohens d demonstrated several instances where performance changed with moderate and large magnitudes. As such, both methods of analysis will be presented and discussed. The following section highlights time-related changes while drawing comparisons within and between samples (schoolboy vs. academy batters). The structure of experimentation allows BATEX to be split into equal periods of 15 overs. In the first 15 overs, 10 overs of activity were completed at low- to moderate-intensity, while the remaining five were high-intensity. In contrast, the second period contained 10 high-intensity and five moderate-intensity overs. It could be argued then, that overs 1-15 correspond with moderate-intensity exercise and overs 16-30 to high-intensity exercise. As such, the discussion will be centred on this comparison (overs 1-15 vs. 16-30).

The author would like to acknowledge the limited literature that has investigated prolonged intermittent physical activity and its effects on cognitive performance. Where prolonged literature does exist, the exercise modality has often been constant rate workloads in either cycling or running. These purely physical modalities lack the cognitive component inherent in batting, and as such, comparison to these data may be misplaced. Nonetheless, comparison with existing literature is paramount. For this reason the subsequent discussion applies comparisons from acute and prolonged bouts of purely physical activity to that of the present results, and where possible, to literature that has both prolonged physical and cognitive components.

7.1.1 Visual Attention/Vigilance

The non-significant decrement in response time in addition to moderate and small effect sizes (schoolboy: $d = 0.56$; academy: $d = 0.02$; academy *retest*: $d = 0.01$) suggest that visual attention in both samples is unaffected by prolonged batting. This result is similar to previous exercise-related investigations that studied the effects of acute bouts of exercise on cognition (McMorris et al., 2003; Audiffren et al., 2008; Draper, McMorris, & Parker, 2010). Additionally, accuracy rates were also unaffected over time (schoolboy: $d = 0.06$; academy: $d = 0.23$; academy *retest*: $d = 0.15$). At a similar intensity to the present investigation, Ashnagar et al. (2014) demonstrated that 20 min of submaximal cycling at 70 $\%HR_{max}$ had no effect on visual choice response times. The average exercise intensity of Ashnagar and colleagues investigation is similar to those of this study, and when taken together suggest that intensities approximating 70 $\%HR_{max}$ have no effect on visual attention in both acute and prolonged settings.

The current results support past research trends, where the magnitude of the effect inferred on vigilance is deemed to be intensity-dependent (McMorris et al., 2003; Davranche et al., 2005; Audiffren et al., 2008; Luft et al., 2009; Ashnagar et al., 2014). In the present study, changes over time show a slowing in processing speed in both samples, however, the magnitude of slowing was higher for schoolboys and different between batting intensities. These skill-related differences may be due to a higher degree of autonomy in the academy batters information processing ability (Hillman et al., 2000; Hatfield et al., 2004; Taliep et al., 2008) which may have allowed academy batters more time to facilitate decision making thereby improving processing speeds. In schoolboy batters, visual attention decreased by the greatest magnitude in the final 15 overs (Table LXV). In contrast the largest decrements in response time and accuracy for academy batters occurred in the first 15 overs, whereafter, both response time and accuracy improved.

In addition, this study shows that the changes in vigilance could also reflect differences in sample characteristics. While academy batters became faster (+10.2 ms) in the final 15-overs, this was not the case for schoolboy batters, who showed a decrement (-32.8 ms) in response time. This result is similar to that of Budde et al. (2012), who observed improved selective attention in participants with higher training statuses. At higher intensities previous studies have demonstrated improvements in vigilance, supporting the results obtained in academy batters. Kashihara & Nakahara (2005) demonstrated that 10 min of cycling at lactate threshold improved post-exercise vigilance, while Pesce et al. (2003) also observed improvements in vigilance following an acute bout of cycling at 60 $\%VO_{2max}$[9]. These two studies provide evidence that vigilance is improved by acute bouts of exercise at moderate- and high-intensities. Audiffren, Tomporowski, & Zagrodnik, (2008) assessed vigilance during and after 40 mins of cycling at 90% of lactate threshold, and also reported facilitative effects on choice response time during exercise (*p*<0.05) but no changes after exercise. When considering this literature it seems that moderate to high-intensity exercise has a

---

[9] Exact exercise duration was not reported by Pesce et al. (2003)

facilitative effect on vigilance, while low-intensity activity has no effect. Greig et al. (2007) demonstrated that a 90 minute intermittent treadmill protocol facilitated response times and decreased error rates in semi-professional soccer players. This result indicates that vigilance is also improved by prolonged intermittent exercise. While vigilance was unaffected in academy batters and moderately impaired in the schoolboy cohort of the current study, it is possible that the added cognitive demands required in batting reduced the facilitative effects demonstrated by Greig and colleagues. The present results could also indicate that the benefits of physical activity are dependent on an athletes' training status. This idea will be elaborated throughout the discussion and critically evaluated in section 7.7.

The short duration of the *identification* task is no doubt a limitation when discussing vigilance, and as such the application of the results may be limited. Nonetheless, accuracy results show that over time and with increased batting duration, batters are more prone to errors and lapses in concentration. While batting it is imperative that batters remain vigilant, making sure that attention is afforded only to the most pertinent visual information (Müller & Abernethy, 2006). From batting occlusion studies, when high vigilance is combined with efficient information pick-up (pre-delivery cues from bowlers), bat-ball interception is improved and batting success increases (Land & McLeod, 2000; Müller et al., 2006; Mann et al., 2010; Sarpeshkar & Mann, 2011; Müller, Brenton, Dempsey, Harbaugh & Corinne, 2015). Therefore, visual attention plays a pivotal role in successful bat-ball interception. Increasing lapses of concentration combined with slower response times could, therefore, have severe implications for competition, where these could easily result in the batter losing their wicket. In instances where multiple batters experience reduced visual attention and wickets are lost at regular intervals, the nature of the game will change which may result in loss of the match. Future studies should look to implement longer duration vigilance tests to investigate the effects of prolonged batting on visual attention.

The progressive increase in visual attention during academy *retest* suggests that either (i) a task learning effect is present or, (ii) that the fatigue experienced by batters was not sufficient to supress visual attention. While the learning effect hypothesis contradicts the findings of Falleti and colleagues (2006), this will be further elucidated in section 7.7.

7.1.2 Psychomotor Functioning

Prolonged intermittent batting induced small deteriorations (d = 0.37) in the psychomotor function of schoolboy batters, with no *battery effects* observed in academy batters (p>0.05; d = 0.01). In spite of these changes in response times, accuracy was not impaired in either sample. The slowing of responses (12.6 ms in schoolboy's) over time is consistent with previous investigations that implemented acute bouts of high-intensity cycling (Ando et al., 2005; Brisswalter et al., 1995; Cote & Salmela, 1992; McMorris et al., 2005). However, there is a larger body of evidence that shows acute exercise of a purely physical nature improves response times when intensity is moderate to high (Davranche et al., 2005; 2006; Kashihara & Nakahara, 2005; Audiffren et al., 2008; Chang et al., 2009). Similarly, during prolonged cycling at 70% peak power output and 75% maximal work capacity, reponse times also improved (Serwah & Marino, 2006 and Hogervorst et al., 1996, respectively). No studies, to the author's knowledge, have examined the effects of prolonged cognitively demanding exercise on psychomotor function.

The current results do not support the intensity-related changes in performance as established by previous studies. This is likely due to the added cognitive components required while batting. At low-moderate intensities, research has demonstrated improvements in response times (Chmura et al., 1998; Davranche & Audiffren, 2004; Davranche et al., 2005, 2006; Serwah & Marino, 2006) while at high intensities others have shown no change in response times (Collardeau et al., 2001; McMorris et al., 2003; Lemmink & Visscher, 2005) and at times impairment (Ando et al., 2005; McMorris et al., 2003; McMorris et al., 2005). In the current results there is no clear trend regarding changes in response times after low-moderate intensity batting. In the first 15-overs (*during*) processing speeds were impaired in schoolboy batters but improved in academy batters. In the final 15 overs response time slowed in both samples (greater impairment in academy batters). The decrement in response times following high-intensity exercise is supported by studies that investigated the effects of acute high-intensity incremental cycling (Cote & Salmela, 1992; Brisswalter et al., 1995; Ando et al., 2005; McMorris et al., 2005). While intensity of exercise is no doubt an important mediator of cognitive improvement; it is possible that the semiautonomous, cognitively-undemanding nature of laboratory running and cycling is a large contributor to the improvements demonstrated in previous investigations. Conversely, it is likely that the cognitively demanding nature of batting mediates the lack of improvement in psychomotor function.

Additionally, the design and formulation of the BATEX protocol used professional/ international matches, workloads and intensities. As a result, its application in an amateur sample may produce a workload that the current sample is unaccustomed to; providing a basis for the impairment in psychomotor functioning after 15 and 30 overs respectively. This could have produced a situation where the current sample may have fatigued more quickly, compared to international players, expediting cognitive decline. Interestingly, the decline for academy batters was less in the first 15 overs when compared to schoolboy batters. Resultantly, the higher level of experience and perhaps higher training statuses of the academy batters could have delayed cognitive impairment. This highlights the importance of experience-appropriate demands when assessing batting performance. Future studies should bear this in mind.

While the changes in psychomotor function appear minimal; in a dynamic time constrained task such as batting, the need for fast and efficient processing speed is paramount. Therefore, even minor changes in response times have large performance implications. For example, if an approaching delivery is travelling at 120km.h^{-1}, the ball would cover approximately 3.3 m in 100 ms. During the 12.6 ms decrement experienced by schoolboy batters (Table LXVI) a cricket ball travelling at 120km.h^{-1} would cover 0.42 m. In this time period, and particularly if batters are fatigued, poor motor control will not allow the batter to optimally position the body resulting in a delayed bat-swing. This will very likely produce a situation where the quality of interception will degrade and the potential to miss the approaching ball will increase. Such situations could result in a higher number of miss hits, complete misses and ultimately a batter losing their wicket. This exemplifies the time constrained nature of batting and the importance of psychomotor function. Furthermore, if a situation arises where visual attention is also reduced (as in the schoolboy sample in the current study) the chance of failing at batting increases further. Therefore, the need for efficient communication between the perceptual and neuromuscular systems is of utmost importance in successful batting, which supports the claim of Sarpeshkar & Mann (2011).

The decrement in psychomotor function was both small (d = 0.37) and it failed statistical significance (p>0.05). In spite of this, the example above demonstrates the implications of even the smallest decrement in batting performance. This may suggest that an alternative means of statistical analysis and interpretation of data may be needed in time constrained tasks such as batting. Noteworthy, the psychomotor task in the current test battery is not a cricket-specific test and thus this interpretation must be taken cautiously.

Once again, in the *retest phase*, academy batters did not experience the same decrement observed in *test phase* or by that of schoolboy batters. Rather, the small decrements observed in the final 15 overs of the *test* session were annulled and performance improved over time. From the current results it appears that training status, batting experience and age play a pivotal role in psychomotor performance. In this regard, lower training status elicits a higher physiological demand and resultantly response times are impaired by larger magnitudes. The implications of age are less clear, warranting further investigation.

7.1.3 Memory

7.1.3.1 Working Memory

Over time, the working memory of academy batters was unaffected ($p>0.05$) by prolonged intermittent batting. While no studies have investigated the effects of prolonged intermittent exercise on working memory, Coles & Tomporowski (2008) found that short-term and working memory was unaffected following 40 min of moderate intensity cycling (60 $\%VO_{2max}$). In contrast, the deterioration in accuracy of working memory of the schoolboy batters following 15 ($d = 0.52$) and 30 overs ($d = 0.61$) is supported by McMorris et al. (2011), who contend that moderate intensity exercise (50-75 $\%VO_{2max}$) impairs response accuracy. The reduced accuracy is also supported by the work of Luft et al. (2009), who reported reductions ($p>0.05$) in accuracy of working memory following a maximal test to volitional exhaustion. While the speed and accuracy of academy batters remained unchanged statistically, batters were slightly faster over time. McMorris et al. (2003) established a similar facilitative effect of incremental exercise on speed of processing in working memory tasks, while other researchers have reported similar results (Tomporowski et al., 2005; McMorris et al., 2011; Smith et al., 2010). While the nature and intensity of the current investigation was different to Soga, Shishido, & Nagatomi (2015), these researchers found that speed and accuracy of working memory were also marginally improved after moderate treadmill walking at 60 $\%HR_{max}$. At higher intensities (60 $\%VO_{2max}$), Tomporowski & Ganio (2006) demonstrated an improvement in response time and accuracy following 40 min of exercise.

Similarly, Luft et al. (2009) observed an improvement in processing speed in the *one back* task (*p*<0.05) following a maximal oxygen consumption test. These results reaffirm the intensity-dependent relationship of cognitive changes in response to exercise.

Working memory performance also indicates sample-related differences, where the differing relative-intensities affected schoolboy batters to a greater degree than academy batters. While both samples experienced a reduction in response accuracy in the first 15 overs, academy batters showed higher accuracy rates and improved response times. Furthermore, when batting intensity increased, academy batters were able to improve speed and accuracy, whereas schoolboy performance deteriorated further. Thus, age, experience and training status impact working memory and its functions. Hansen et al. (2003) believe that working memory is essential in computational processing, storage and retrieval of information that has been stored within memory. Working memory is of paramount importance if batters are to successfully interpret environmental information, analyse bowler and ball characteristics and select the most appropriate shot to play. Therefore, it could be argued that the reductions in the working memory of schoolboy batters could affect decision making, where batters of this calibre may be more likely to lose their wicket when match intensity and duration of batting, increases.

Based on performance changes within academy batters, this is the first task that does not demonstrate learning effects during *retest* (Table LXVII). During *retest*, academy batters experienced lower response accuracy with similar response times. This is especially evident in the final 15 overs. The reductions in overall accuracy may be the result of improved response time, where academy batters were on average 27.2 ms faster in the final 15 overs of *retest* compared to the *test* session (16.8 vs. 44.0 ms). This could, potentially, explain the higher inverse efficiency score and why performance did not improve over time.

7.1.3.2 Visual Learning and Memory

The *One Card-learning* task was unable to detect changes in visual learning and memory (*p*>0.05) which is a result also reported by Luft et al. (2009). Within this task, both schoolboy and academy batters were able to maintain accuracy over time (*p*>0.05; *d* = 0.01 and *p*>0.05; *d* = 0.17, respectively) while academy batters also improved speed (*p*>0.05; *d* = 0.50). The improved speed and accuracy of academy batters is supported by the findings of Coles & Tomporowski (2008), who observed improvements in recall after 40 min of moderate intensity cycling (60 %VO_{2max}) but no beneficial effects in short-term or working memory. The improvement in accuracy in the current study suggests that the capacity and retrieval processes of academy batters were not impaired by prolonged intermittent batting. This begs the question: why did schoolboy batters not experience similar improvements in speed and accuracy? It is known that complex cognitive processes, like memory, invoke higher brain centres to facilitate processing (Purves et al., 2004). According to Dietrich's (2009) model of hypofrontality, when cognitive fatigue is present and recourses are low, higher brain regions are the first that will experience signs of impairment. Furthermore, brain development in these regions is only fully matured late in the second decade of life (Knapp & Morton, 2013). It is possible then, that the differences in development (age [$p<0.01$] and playing experience [$p<0.01$]) could explain the differences between samples. Moreover, the greater physical and cognitive strain imposed by BATEX and the, perhaps, less developed higher brain regions of schoolboy batters could explain why these batters were unable to improve visual learning and memory performance like academy batters.

As proposed in previous studies, the changes in performance in visual learning and memory in both samples can be described as an inverted-U function (Yerkes & Dodson, 1908). In the first 15 overs and when compared to *baseline*, accuracy improved in both schoolboy ($p<0.05$; $d = 0.33$) and academy batters ($p<0.05$; $d = 0.24$). In each of these instances, the accuracy improvement in the first 15 overs was accompanied by faster response times and as a consequence, a speed accuracy trade-off is not evident. In the final 15 overs, accuracy decreased in both samples to levels comparable to *pre-test*. This performance function is closely related to physiological arousal, where optimal performance coincides with optimum arousal (Kamijo et al., 2004; Chang et al., 2009; Lambourne & Tomporowski, 2010). This will be unpacked at a later stage in the discussion (7.7). It is also possible that the initial increase in accuracy in the first 15 overs could be a task learning effect (Bartels et al., 2010) However, the similar trend in the accuracy results produced in the academy *retest* session suggests performance changes after moderate intensity batting was not a once-off effect, but rather the result of activity-induced arousal.

The decrements in response accuracy for schoolboy and academy batters (2% vs. 1%, respectively) in the final 15 overs coincided with faster processing speeds (52.6 and 88.8 ms, respectively). Therefore, it is possible that a speed accuracy trade-off could explain the decrement in performance in the last 15 overs (*post-test*). In spite of the larger decrement in schoolboy's speed and accuracy responses, the inverse efficiency score suggests that schoolboy batters had better overall performance. This could be due to accuracy performance. Bruyer & Brysbaert (2011) state that where the accuracy of performance is less than 90%, the inverse efficiency score is a poor measure for overall performance. Accuracy rates in the *One Card-learning* task were 69% in schoolboys and 75% (*test*) and 77% (*retest*) for academy batters. Accordingly, the higher efficiency score in schoolboy batters was mediated by their faster response times. However, the primary outcome variable in this task was accuracy therefore, performance in schoolboy batters was impaired to a greater extent. As such, the inverse efficiency score for this task should be interpreted with caution.

In considering the variability in responses, inter-individual variability in speed and accuracy was lowest after 15-overs (in both samples), whereafter variability increased *post-test*. This highlights the importance of inter-individual variability and how prolonged batting affects players differentially. Collectively, the maintained accuracy in schoolboy batters and the improvement observed in academy batters, suggests that visual learning and memory could be stimulated in prolonged setting. It is possible then, that the utilisation of visual information over the course of an innings could be improved with increasing time at the crease. The improved batting accuracy of schoolboy batters confirms this hypothesis, where accuracy was highest in the final over of the simulation. This highlights the importance of batting-specific tasks that increase task-specific perception-action coupling when assessing batting performance. It also questions the use of seated cognitive assessments when measuring information processing performance in a demanding, highly dynamic, task like batting.

7.1.4 Executive Functions

The reduced executive function of schoolboy batters lacks support from literature, where both Sibley et al. (2006) and Yanagisawa et al. (2010) demonstrated that acute bouts of cycling at 50 $\%VO_{2peak}$ improved response time with no detrimental effects observed in response accuracy. Improvements in response accuracy and time have also been reported in the Stroop and Paced Auditory Serial Addition tasks when long duration (60-100 mins) cycling was the exercise modality understudy (Hogervorst et al., 1996; Tomporowski et al., 2005). The associated intensity of exercise in these studies was 75% maximal working capacity and 60 %VO_{2max}, respectively. The discrepancies in findings again show that the cognitively demanding nature of batting is likely a confounding factor in performance changes in response to prolonged exercise.

While the improvement in speed of schoolboy batters does accord with previous literature, error rates are the defining outcome variable in the *maze* task and as such performance is significantly reduced. Similar results were reported by Del Giorno et al. (2010), who found that 30 min of cycling at lactate threshold impaired executive control, producing higher total error and preservative error rates. According to Pietrzak et al. (2008) this decrement in schoolboy *maze* performance (*pre* vs. *post*: p=0.19; d = 0.62) could represent disruption in the coordination of visuomotor and visuoperceptual functions, or the executive processes that encode and manipulate spatial information. Furthermore, it could be caused by an integrated disruption of these domains. Over the same time period, academy batters committed similar error rates, however, the decrement over time did not achieve statistical or practical significance (p>0.05; d = 0.02). Therefore, academy batters executive task performance was unaffected by prolonged intermittent batting and supports the data of Kamijo et al. (2004) and Kamijo and colleagues (2006), who reported unchanged executive function after moderate and high-intensity cycling. The discrepancy in executive performance between schoolboy and academy batters support the earlier notion that the cognitive demands associated with batting affect performance to a lesser degree if the batter is more experienced.

The higher number of errors made by schoolboy and academy batters after exercise is supported in the results of Del Giorno et al. (2010). These authors also reported higher rates of preservative errors (2 consecutive errors) following exercise, a result also observed in the current study. Both schoolboy and academy batters committed greater perseverative errors in the final test battery and in addition, the number of rule break errors were also higher in the final 15 overs of batting (Table LXX). Pietrzak et al. (2008) contend that errors of this nature represent inhibitory errors and the executive process of error monitoring. In a sport such as cricket, batting is highly dependent on minimising errors. Therefore, if batters are prone to a greater frequency of errors in executive control or decision making, batters will fail at their task and get out. Therefore, given the decrement in performance of schoolboy batters in total, rule-break and perseverative errors, it is very likely that batters of this calibre will fail to maintain batting performance in a prolonged setting. In contrast, the lack of change in responses and the fewer perseverative errors in the academy sample, propose that these batters are better able to maintain executive control during prolonged cognitively demanding batting periods. These batters are, therefore, less likely to lose their wicket.

7.1.5 Summary

This section has highlighted several hypotheses explaining cognitive performance changes found in batting. Firstly, changes in cognitive performance in response to prolonged batting seem to be, like other studies, dependent on the intensity of exercise. Secondly, the added cognitive component inherent in batting seems, in some instances, to mitigate the beneficial effects of exercise. Lastly, the mitigation of these effects seems to be related to the batters experience, age-related developmental effects, or perhaps the level of coaching the batter has received.

7.2 Heart Rate and Heart Rate Variability

This section seeks to understand the time-related changes in heart rate parameters before batting (*pre-test* effects) as well as after 15 overs (*during*) and 30 overs (*post-test*) of batting. Data are discussed in terms of *battery effects* (average change during the test battery) and *task effects* (average change within each task during a particular cognitive battery). These distinctions provide practical value, as we can determine recovery rates and perhaps understand the modulation of the cardiovascular system following exercise. Furthermore, we can begin to understand how these changes affect a batter's ability to respond to tasks designed to impose cognitive stress. *Battery* effects will show the effects of prolonged batting on post-exercise recovery/modulation and potentially how effort regulation changes over time. Alternatively, *task effects* detail autonomic modulation between tasks and provide information with respect to cognitive workload between tasks. The results from each will provide insight regarding the mechanisms of performance adaptation.

7.2.1 Pre-Exercise Effects

Each *pre-test* cognitive battery provides baseline measures of heart rate parameters and reflects performance without any influence of physical activity. As observed during habituation, schoolboy batters had lower reference heart rates (65 ± 10 bt.min^{-1}) when compared to academy batters (70 ± 8 bt.min^{-1}). Heart rates during *pre-test* assessments were similar to those obtained in habituation, where schoolboy batters had lower heart rates throughout the *pre-test* cognitive battery. No task-related differences (p>0.05) in heart rate were observed during *pre-test*, a result observed in both samples and during *retest* in academy batters*.* *Pre-test* responses indicate that schoolboy batters displayed lower *battery-* and *task*-related time domain and frequency spectrum components. The between-task trends were the same in both samples, where heart rate variability increased as task battery duration increased (*time-on-task effect*). Also, in each sample, the *maze* task induced the lowest variability in heart rate.

The increase in SDNN and RMSSD between the *maze* and *one-back* tasks in schoolboy (25% [p<0.05] and 26% [p<0.05], respectively) and academy batters (*test*: 20%, respectively) indicate that mental workload was highest in the *maze* task (Hjortskov et al., 2004). This finding is in accord with previous research that has shown lower SDNN and RMSSD in tasks that require higher mental workload (Luft et al., 2009; Mukherjee et al., 2011; Prinsloo et al., 2011; Taelman et al., 2011; Mateo, et al., 2012; Cinaz et al., 2013). Furthermore, it shows that over time mental workload diminishes and that parasympathetic modulation increases with time on task (Stein et al.,1994; Buchheit, 2014). The 3% increase in SDNN and 2% increase in RMSSD in the *retest* academy session was less than the *test* academy session, however, changes in this sample were not significant (p>0.05) in either session (*test* and *retest*). The absence of difference in heart rate parameters between the two high-order tasks in the current battery (*maze* and *one card-learning* task) also supports the workload theory above. Additional support is found in the significantly (p<0.05) reduced high-frequency power of schoolboy batters between the *maze* task and all other tasks. Here previous studies have shown that tasks which require higher degrees of executive control elicit decreases in frequency spectra (Berntson et al., 1997; Malik et al., 1996; Luft et al., 2009) - specifically high-frequency power (Luque-Casado et al., 2015). Also, the continual increase in the frequency spectra of schoolboy batters over time, shows that mental workload diminished between the first and last task (Jorna, 1992; Nickel & Nachreiner, 2003). The increases in low- and high-frequency power and the resultant decrease in %LF power of schoolboy batters, indicates sympathetic predominance throughout the test battery with increasing parasympathetic activation over time (Al-Ani et al., 1996; Malik et al., 1996; Berntson et al., 1997; Hansen, Johnsen, & Thayer, 2003; Elliot et al., 2011; McDuff, Gontarek, & Picard, 2014). Similarly, despite continual decreases in both low- and high-frequency power in academy batters *test* and *retest* sessions, the decreasing %LF power also demonstrates sympathetic predominance with increasing parasympathetic activation over time. These data confirm that the CogState test battery applies differential workloads for each task, and that these can be detected by changes in heart rate variability.

When considering the magnitude of differences, the largest differences were observed between the *maze* and the *one-back* task in both academy and schoolboy batters. This suggests a *time-on-task effect* where heart rate variability increases with increasing task duration. *Time-on-task effects* are also reported by Jorna (1992) and Luque-Casado et al. (2013), however, these studies show that heart rate variability and task time share an inverse relationship. Differences in cognitive task structure in the current investigation (five short duration tasks) to the three longer duration (10-15 min) tasks used by Luque-Casado et al. (2013) could account for this discrepancy. Therefore, task duration of cognitive assessments seems important when measuring changes in heart rate.

The significantly lower time domain and frequency spectrum parameters of schoolboy batters in the *maze* task was not paralleled in academy batters (in *test* and *retest*). These sample-related differences show how individual variability can influence heart rate variability. Slower recovery heart rate and higher exercising heart rates are indicative of lower training status (Daanen, et al., 2012). Therefore, based on the heart rate data of schoolboy batters, this sample is less trained than the academy batters. Therefore, the higher reference heart rate variability in schoolboy batters contradicts previous literature (Corrales et al., 2012; Luque-Casado et al., 2013; Peçanha et al., 2013 Alderman & Olson, 2014) who contend that athletes of higher training status have higher reference heart rate variability.

Table LXXII: Pearson correlation analysis of *pre-* and *post-test* heart rate and heart rate variability (*pre-test* reference heart rate = resting heart rate obtained during habituation; *post-test* reference heart rate = heart rate after the 30th over).

	PRE-TEST				***POST-TEST***			
	RHR vs. SDNN	***RHR vs. RMSSD***	***RHR vs. HF Power***	***RHR vs. LF Power***	***RHR vs. SDNN***	***RHR vs. RMSSD***	***RHR vs. HF Power***	***RHR vs. LF Power***
Schoolboy	-0.47	-0.44	-0.32	-0.33	-0.80	-0.79	-0.12	-0.63
Academy Test	-0.31	-0.31	-0.30	-0.29	-0.63	-0.55	-0.41	-0.35
Academy Retest	-0.21	-0.20	-0.24	-0.11	-0.66	-0.63	-0.45	-0.36
Mean	-0.33	-0.32	-0.28	-0.24	-0.70	-0.66	-0.33	-0.45

At rest, the lower reference heart rate and higher reference heart rate variability of schoolboy batters produce larger correlations than those observed in academy batters (Table LXXII). Additionally, the higher exercising heart rates and lower heart rate variability responses *post-test* in schoolboy batters also show stronger correlations than academy batters. Therefore, the results observed at rest in combination with those recorded after batting, suggest that reference heart rate variability may be more closely correlated to reference heart rate and less so with training status. The stronger mean correlations of the time domain parameters suggest that time domain parameters are more strongly correlated with reference heart rates. This provides support for a previous investigation where time domain parameters were found to be the most reliable parameter in the assessment of mental effort (Mukherjee et al., 2011). While further analysis of this nature is beyond the scope of the current study, future investigations should look to explain this relationship.

In conclusion, *pre-test* results disclose two important findings; first, the tasks within the cognitive battery imposed differential effects on heart rate variability, indicating a well-structured and mentally demanding test battery. Second, cognitive workloads were different between samples, with academy batters investing more effort during the *pre-test* cognitive battery.

7.2.2 The Impact of BATEX on Heart Rate Variability

The known suppression of parasympathetic activity and increased activation of sympathetic pathways during physical activity (Thibodeau & Patton, 1999; Tortora & Derrickson, 2005; Baechle & Earle, 2008) means that the increase in heart rate and the corresponding decrease following cessation of batting were expected. These changes in sympathovagal balance during exercise maintain cardiac output to ensure blood flow to the organs and working muscles (Javorka et al., 2002; Daanen et al., 2012). After exercise has been terminated, changes in autonomic regulation bring about reductions in heart rate, breathing frequency, cardiac output and blood pressure (Halliwill, Buck, Lacewell, & Romero, 2013) which directly influence heart rate variability (Peçanha et al., 2013). It is not surprising then, that in the time period following batting cessation and the start of cognitive testing that mean heart rate decreased. The reduction in heart rate is a result of centrally mediated decreases in sympathetic nerve activity and concomitant increases in vagus nerve excitation (Halliwill et al., 2013). Recovery rates of schoolboy and academy batters were similar after 15 (30%

respectively) and 30 overs (34 and 37%), while in the *retest* academy session, recovery equated to 29 and 37% for the same comparisons. Although the time between batting and task initiation was not measured, it appears that participants had adequately recovered by the onset of cognitive testing. Recovery of this magnitude is important in heart rate variability data analysis and interpretation, as this reduces the non-stationarity of the data (Jorna, 1992; Taelman et al., 2011). The increase in heart rate with batting and the accompanying downregulation following batting cessation had large influences on time domain and frequency spectrum parameters.

7.2.2.1 Battery Effects

In schoolboy and academy batters the progression of the simulation brought about increases in heart rate ($p<0.05$) and decreases in time domain parameters ($p<0.05$) (Table XXIV, Table XLIX). Heart rate was highest and heart rate variability was lowest *post-test*. While not assessed statistically, heart rates at the start of the *post-test* battery were higher in schoolboy batters compared to academy batters (*post-test*: 101 ± 10 vs. 94 ± 9 bt.min^{-1}, respectively). The lower heart rates in academy batters are likely due to the longer time frame between batting cessation and cognitive testing in *phase 2* and *3*. This is because academy batters had to perform vertical jump height, whereas schoolboy batters did not.

In both samples, increased heart rate reduced the time between N-N intervals, subsequently reducing SDNN, RMSSD, PNN50 as well as low- and high-frequency power. The exercise-induced decreases in low- and high-frequency power are supported in previous literature (Kamath, Fallen, & McKelvie, 1991; Freeman et al., 2006; Peçanha et al., 2013), as are the reductions in SDNN, RMSSD and PNN50 (Javorka et al., 2002; DiDomenico & Nussbaum, 2011). These reductions in heart rate variability are believed to be induced through vagal withdrawal and increased sympathetic activation of the sinoatrial node as exercise duration and intensity increase (Hjortskov et al., 2004; Kamath et al., 1991; Luft et al., 2009; Peçanha et al., 2013).

The degree of change in heart rate variability responses was also dependent on the nature of exercise and the accompanying intensity (Casonatto et al., 2011; DiDomenico & Nussbaum, 2011). The greater sensitivity demonstrated in the time domain measures in the current study was also observed in the results of Mukherjee et al. (2011). Differences in responses between overs 15 and 30 are likely related to the prolonged nature of BATEX and the intermittent intensity between stages. DiDomenico & Nussbaum (2011) demonstrated that the type of activity (whole body vs. isolated movements) and the frequency of movements dictate the magnitude of decrease in heart rate variability. The results in the present study support this theory. While the largest change was observed between *pre-test* and the 15th over of batting, the increased running frequency in the final 15 overs produced further decreases in heart rate parameters. In schoolboy batters the increases in LF:HF ratio ($p<0.01$) and %LF over time (66% [*pre-test*], 78% [*during*; $p<0.01$] and 78% [*post-test*; $p<0.01$]) indicate sympathetic predomination. Similar increases were observed in academy batters during *test* (66%, 75% [$p<0.01$], 79% [$p<0.01$]) and *retest* (63%, 72% [$p<0.01$], 78% [$p<0.01$]). Resultantly, the frequency spectra of both academy and schoolboy batters indicate increased sympathetic activation (Pagani et al., 1986; Montano et al., 1994; Al-Ani et al., 1996; Taelman et al., 2011,) where arousal was elevated after 15 overs and highest at the end of the simulation. Given long standing exercise physiology principles and previous research that demonstrate reductions in parasympathetic activation with physical activity (Hjortskov et al., 2004; Elliot et al., 2011; McDuff, Gontarek, & Picard, 2014), this result was expected.

Not directly supported by the current results is the intensity-related change in heart rate variability, observed by Casonatto et al. (2011). These authors demonstrated that 30 min of high-intensity activity (80 $\%VO_{2max}$) produced the greatest reductions in RMSSD and frequency spectra. While the current data show a larger reduction induced by high-intensity activity, the time domain and frequency spectrum responses were not significantly different ($p<0.05$) to parameters measured after moderate-intensity activity. This is likely due to the higher intensity tested by Casonatto et al. (2011) and potentially the shorter duration. Casonatto and colleagues (2011) had participants complete 30 min of high-intensity activity, whereas BATEX required 70 min of moderate-intensity activity and a further 70 min of high-intensity running. Therefore, changes in heart rate variability are also sensitive to activity duration.

Non-exercise-related research would contend the reduction in time domain and frequency spectra indicate increased cognitive workload and effort over time (Hjortskov et al., 2004; Taelman et al., 2011; Mukherjee et al., 2011; Mateo, et al., 2012; Luque-Casado et al., 2013; Cinaz et al., 2013). The increased sympathetic activation would also support this notion, where cognitive stress evokes elevated sympathetic activation (Staal, 2004). While the addition of physical activity does indeed complicate the application of this dogma to the interpretation of the current results, these theories must be considered. This will be done in the integrated discussion (7.7).

The only sample-related difference was observed in frequency spectrum responses, where in academy batters, low-frequency power was not different over time ($p>0.05$): rather, high-frequency power was reduced ($p<0.05$). The opposite was demonstrated in schoolboy batters. Importantly, time domain and frequency spectrum responses of academy batters were replicated in the *retest phase* of experimentation. While this section has laid a good foundation to explain performance changes, the mechanism of performance deterioration is not yet clear. To isolate performance changes to mental effort or physiological arousal, it is important to understand the task-related changes in heart rate variability. This will provide insight into the mechanisms of performance adaptation which can inform performance decrement.

7.2.2.2 Task Effects

With fewer main effects observed in task-related differences, and with the lack of a clear trend in the frequency data, the interpretation of *task effects* is difficult. Noteworthy, a *time-on-task effect* describes the change in heart rate parameters from the onset of the cognitive battery (*maze* task) until its completion (*one-back* task). *Time-on-task effects* ($p<0.05$) were observed for heart rate in all batteries for schoolboy and academy batters. Heart rate recovery during each 15-minute battery was as follows; schoolboy batters: 3% *during* and 11% *post-test*; academy batters: *test* – 8% and 7%, respectively and *retest* – 6% and 7%. Despite adequate recovery from batting before the onset of cognitive testing, decreases in heart rate indicate that recovery was still taking place during each cognitive battery. As such, it is expected that parasympathetic activation increases over time.

The increases ($p<0.05$) in SDNN, RMSSD and PNN50 of schoolboy and academy batters following exercise mirror the results of Javorka et al. (2002). In schoolboy batters, SDNN and RMSSD increased by 55% and 54% between the *maze* and *one-back* task (after 15 overs) and by 152% ($p<0.05$) and 157% ($p<0.05$) *post-test*. Over the same period in academy batters, changes in heart rate variability were as follows; after 15 overs SDNN and

RMSSD increased by 53% ($p<0.01$) and 55% ($p<0.01$) (respectively), and by 59% ($p<0.02$) and 3% after 30 overs ($p<0.02$). Thus, *time-on-task effects* in time domain results are also present, a result consistent with others (Jorna, 1992; Luque-Casado et al., 2013). Jorna (1992) states that a *time-on-task effect* has an inverse relationship to heart rate variability – a concept supported by Luque-Casado et al. (2013). Taelman et al. (2011) describe a *time-on-task effect* as the autonomic nervous system's response to stress, where, the initial rise in heart rate variability is a "stress response" whereafter responses are reduced and stabilise. The theory of Taelman and colleagues and Luque-Casado's research group are opposed in the current results, where heart rate variability was shown to increase over time ($p<0.05$). The most obvious difference between the current study and that of these authors' was the addition of physical activity in the current study. An investigation that measured heart rate parameters following exercise found similar increases in SDNN and RMSSD during post-exercise recovery; resultantly the current findings gain support from Javorka et al. (2002). This again demonstrates the impact of physical activity on heart rate parameters.

Additionally, non-significant ($p>0.05$) *time-on-task effects* were also found in the present frequency spectra. In schoolboy and academy batters and across all test batteries, frequency results were not different over time ($p>0.05$) and no task-related differences were apparent. With one or two exceptions, the general trend in frequency spectra show increasing power with *time-on task*: a finding supported previously (Kamath et al., 1991; Javorka et al., 2002; Peçanha et al., 2013). Therefore, notwithstanding the different trends in power spectra between schoolboy and academy batters, both sample responses indicated decreasing %LF power (LF/HF) and a lower LF:HF ratio as *time-on-task* increases. According to previous literature, these represent modulation of the autonomic nervous system (Malik et al., 1996; Berntson et al., 1997; Carter et al., 2003; Burr, 2007) indicating an overall sympathetic predomination with increasing parasympathetic activation with *time-on-task* (Pagani et al., 1986; Jorna, 1992; Malliani, Lombardi, & Pagani, 1994; Al-Ani et al., 1996; Berntson et al., 1997; Freeman et al., 2006). It appears then, that increasing parasympathetic modulation potentially reduces cognitive performance over time, particularly in schoolboy batters. This supports traditional (non-exercise-related) literature where increased time domain measures reflect reduced cognitive workload over time (Hjortskov et al., 2004; Taelman et al., 2011; Mukherjee et al., 2011; Mateo, et al., 2012; Luque-Casado et al., 2013; Cinaz et al., 2013). It also suggests that the removal of the batter from their batting environment for cognitive testing is not a true reflection of performance.

Moreover, parasympathetic activation may not increase if cognition is assessed while batting, and as a result performance might not degrade. Therefore, and as mentioned earlier, future studies should look for alternative means of cognitive assessment where the physiological modulation will be more representative of batting.

The battery-related decrease and post-exercise task-related increase in low- and high-frequency power of schoolboy batters are in accord with exercise-related literature (Kamath et al., 1991; Jorna, 1992; Berntson et al., 1997; Javorka et al., 2002; DiDomenico & Nussbaum, 2011; Peçanha et al., 2013). Javorka et al. (2002) and Peçanha et al. (2013) contend that decreases in heart rate variability immediately after exercise, are due to the increased sympathetic activity in response to physical activity. Furthermore, they state that, the increase in heart rate variability during recovery is likely due to cardio deceleration and increasing parasympathetic modulation. Due to the similarity of the schoolboy responses to that of Javorka et al. (2002), Kamath et al. (1991) and Peçanha et al. (2013), it is reasonable to apply the conclusions of these studies to the schoolboy cohort. Therefore, it is likely that the present changes in schoolboy batters' heart rate variability with *time-on-task* is related to physical activity and cardio deceleration over time. However, while literature indicates that reduced low- and high-frequency power coincide with increased cognitive effort (Luft et al., 2009; Luque-Casado et al., 2015), it is also reasonable to contend that the *maze* task was afforded greater effort than the *one-back* task.

In contrast, the results of academy batters oppose that of Javorka et al. (2002) and Peçanha et al. (2013), where low-frequency power continued to decrease over time and mixed high-frequency results showed decreases on two occasions. These data, compared to schoolboy responses, suggest that the mechanisms of recovery and hence autonomic modulation are different for players of differing training statuses and/or skill levels. During post-exercise recovery, Peçanha et al. (2013) observed that low- and high-frequency power were consistently lower in athletes of low training status. They found highly trained athletes demonstrated higher ($p<0.05$) low-frequency power from minutes 5-10 of recovery and higher high-frequency power ($p<0.05$) from minutes 6-10. This however, was not the case in the current investigation, where the more highly trained academy batters had lower low- and high-frequency power. Therefore, while the academy batters results oppose those of Peçanha and colleagues, they suggest that the recovery process during cognitive assessments may have been influenced by the cognitive test battery and the differential effects of each task. These differences then disclose two important findings. Firstly, the different methodologies employed show the sensitivity of heart rate variability and how testing procedures may have confounding influences on this parameter. Second, and more importantly, it suggests that the cognitive battery conducted after physical activity may have altered autonomic modulation and that changes in heart rate parameters may be the result of the cognitive tasks. Therefore, the associated changes in heart rate variability parameters may not be solely attributed to cardio deceleration. This finding allows the results to be interpreted through traditional non-exercising theories.

Accordingly, traditional heart rate variability research contends that increased heart rate variability with increasing *time-on-task* is indicative of diminishing mental workload (Hjortskov et al., 2004; Taelman et al., 2011; Mukherjee et al., 2011; Mateo, et al., 2012; Luque-Casado et al., 2013; Cinaz et al., 2013). Furthermore, this literature would suggest that batters became increasingly task averse over time, reducing effort as the test battery progressed. Further interpretation of these theories, suggest that the change in heart rate variability with *time-on-task* could be related to differential task requirements (Nickel & Nachreiner, 2003). In this regard, the higher complexity, and hence attentional resource demands, associated with the *maze* task (in comparison to the *one-back* task) may be a major influence on heart rate variability, potentially explaining *time-on-task effects*. This is supported by the *pre-test* responses of schoolboy batters, where SDNN, RMSSD and high-frequency power in the *maze* task were lower than any other task. However, were this true, it would be expected that differences between the most complex (*maze*) and least complex (*detection*) tasks would also demonstrate changes ($p<0.05$) in time domain measures. This, however, was not the case, with no effects observed between the *detection* and *maze* tasks in any of the variability parameters. Perhaps the elevated sympathetic activation (induced by exercise) during the *detection* task prevented statistical difference between the *maze* and *detection* tasks. Thereafter, the progressive increase in parasympathetic activation may result in decreased arousal, producing more obvious task-related differences. It appears then that the high attentional demand of the *maze* task in the early parts of the test battery can be met because arousal is still elevated. However, as the time-on-task increases and arousal decreases (as evidenced by increased parasympathetic activation) differences between tasks are more apparent. This shows the importance of optimal arousal during cognitive performance where decreasing arousal may result in performance decrement.

The present results demonstrate the intricacies of autonomic regulation and further elucidate on the sensitivity of heart rate variability parameters. It appears that the intricacies of this measure do not allow for a definitive conclusion, where extraneous variables will very likely influence heart rate responses. As such interpretation of results must consider these variables and their potential effect on responses. It also brings into question the use of heart rate variability in studies that aim to investigate the influences of physical activity on cognitive performance. Moreover, only when the batter remains in the batting environment will the ecological validity of cognitive performance be ensured. However, when heart rate variability is assessed during activity, the stationarity of the data will be compromised and as a result so will the validity of the data. It then appears that the combination of these dependent measures is not feasible if cognitive performance is to be assessed during batting.

7.2.3 Effect of Extraneous Variables

Changes in breathing frequency could also account for changes in heart rate variability (Javorka et al., 2002; Carter et al., 2003; Prinsloo et al., 2011; McDuff et al., 2014). Reflective of respiratory sinus arrhythmia, the decrease in high-frequency power could easily be the result of reduced breathing frequency over time. While this was not directly assessed, these changes are very likely within 15 min of post-exercise recovery. Therefore, future studies should incorporate spirometry with cognitive assessments so that this variable can be accounted for during analysis and interpretation of results. In addition, blood pressure changes post-exercise also influence heart rate variability and as such, these should also be monitored during cognitive assessment (Goldberger et al., 2001; Goldstein et al., 2011; Halliwill et al., 2013). When this is done, the results could elucidate the effects of baroreflex activity on heart rate variability. These measures will facilitate further understanding into post-exercise autonomic modulation and the contribution of spirometry and blood pressure changes; thus the resultant effects of the cognitive tasks could also be clarified.

Malliani, Lombardi, & Pagani (1994) contend that where sympathetic excitation leads to tachycardia, heart rate variability will demonstrate a reduction in total power and the standard deviation. Further, the biological relevance of spectral analysis is severely limited when variance is restricted (Malliani, Lombardi, & Pagani, 1994). Such situations are said to include strenuous exercise and diseases like heart failure. In the current study the short time intervals used to assess frequency spectra may limit the reliability of the results.

Evidence of this is seen in the very high inter-participant variability. Furthermore, compared to *pre-test*, the results from the final assessments of *phase 1*, *2* and *3* demonstrate significantly reduced ($p<0.01$) heart rate variability in the frequency components. It is possible then, that the results of the final batteries may not accurately reflect balanced autonomic nervous system activity. Therefore, these results should be interpreted with caution. Further research investigating exercise-related changes in heart rate variability in conjunction with cognitive testing are warranted to better understand this relationship.

Differences in task duration could also contribute to changes in heart rate variability. Jorna (1992) states that measuring heart rate variability for longer periods allows more samples to be collected, thereby improving reliability of the results. On average, batters required approximately four minutes to compete the *maze* task and six minutes to complete the memory task. When compared with the shorter duration of the *detection*, *identification* and *one-back* tasks (± 90 seconds) the former tasks would provide a greater number of samples that could be analysed. Therefore, task duration may have influenced the current task-related findings.

While changes in heart rate variability could be explained by training adaptations, these could also be attributed to differences in the methodologies between phases. Moreover, in schoolboy batters, players began the cognitive test battery approximately 5 min after the 30th over, following body mass measurements (with and without kit). In contrast, academy batters were weighed and completed vertical jump assessments before the final cognitive battery was initiated. Therefore, the time between batting and cognitive assessment was longer in academy batters, and may have influenced the *post-test* heart rate variability results. Furthermore, the greater number of test batteries and the longer duration of experimentation for schoolboy batters may have altered the time course of cognitive fatigue. Resultantly, comparisons with academy batters may be limited; a comparison which was not the main purpose of this investigation. For these reasons statistical analyses between phases was not conducted.

Differences in training status between samples could potentially explain the differences in time domain and frequency spectra over time. Faster recovery rates in academy batters suggest higher efficiency of the cardiovascular system and as a result better balance of the autonomic system. Therefore, these physiological adaptations could account for the differences displayed between samples. Age has also been shown to influence heart rate variability, where older individuals demonstrate lower heart rate variability (Al-Ani et al., 1996; Xhyheri et al., 2012). The lower resting heart rate variability of academy batters supports this notion. It also suggests that age must be considered when quantifying the effects of training status on heart rate variability. While age could account for the differences observed between samples, it is unlikely that a mean difference of one year would result in the changes in heart rate variability. In spite of this, future batting research should look to confirm this.

7.2.4 Conclusions

The present results provide valuable information into cardiovascular regulation before and following exercise. It also sheds light into the complicated relationship between heart rate variability and cognitive workload when physical activity is required. No study to date has examined this relationship. It appears that physical activity alters the relationship between cognitive workload and heart rate variability. While traditional literature shows decreased heart rate variability to reflect increasing cognitive demands, this principle seems to lack application to studies involving physical activity. The increased activation of the autonomic nervous system during and following exercise seems to create a situation where ‘noise’ in each branch of the system interferes with the subtle changes induced by cognitive workload. As such, mental workload cannot be definitively derived through heart rate variability in such situations. The current study discloses important information for future studies and provides a number of methodological considerations going forward.

For the correct application of heart rate variability to studies measuring the effects of physical activity on cognitive performance, researchers should consider the following. Firstly, spirometry and blood pressure should be analysed during cognitive test batteries, as this will inform how baroreflex activity and breathing frequency affect low- and high-frequency power. This would allow researchers to correct for these factors and determine the autonomic regulation induced by cognitive demand. Second, future studies should also use a control condition (not performing cognitive tasks following batting) to determine the natural regulation of heart rate parameters. This should then be compared to an experimental condition where the CogState test battery can be conducted after batting. When this comparison is made, it will allow researchers to isolate the impact of the cognitive test battery and the specific tasks within it. This will also allow issues such as task aversion and cognitive withdrawal to be elucidated.

It is possible that the repeated exposure to the cognitive test battery may have provided a learning effect for academy batters, and could potentially explain the improvement in performance between *test* and *retest* sessions. While these data oppose the results of Falleti et al. (2006), who suggest that learning during CogState is maximal after the second trail of the test battery; they are consistent with the results of McCaffrey et al. (1993), Benedict & Zgaljardic (1998) and Bartels et al. (2010). These authors show that cognitive task learning effects may occur over weeks (Benedict & Zgaljardic, 1998) and even months (Bartels et al., 2010) if the same tasks are continually repeated. It is likely then, that the repeated nature of cognitive testing during *test* and *retest* may have resulted in task learning, explaining the small improvements in psychomotor speed while accuracy was maintained. By contrast, the reduced physiological effort, improved sprint decrement and higher countermovement and squat jump heights suggest that performance regulation was better in the *retest* session. At the same time, academy batters perceived the demand of the second session be lower. Resultantly, the reduced physiological load of the *retest* session could then explain the minor improvements in cognitive performance.

7.3 Physical Responses

The distances covered by the current samples (1865. 2 m at 859.5m.h^{-1}) are dissimilar to the 2171 ±157 m and 2216 ±177 m measured in previous studies that implemented BATEX as the independent test protocol (Houghton et al., 2011b, Houghton & Dawson, 2012, respectively). The higher distance reported by Houghton and colleagues studies' are likely due to measurement differences. The current study calculated distance by multiplication of shuttle distance by total number of shuttles, whereas GPS units were utilised by Houghton and colleagues. The use of GPS was not within the means of the current institution and would not have been possible in an indoor laboratory setting; as a result this may be deemed a limitation of the present study. The work rates reported by Houghton et al. (2011b) are similar to the one-day work rates of Petersen and colleagues' (2010) - 2476 m.h^{-1}. Having replicated the simulation as per the authors instructions, it is anticipated that the current work rate would be more closely aligned to the results of Houghton and colleagues (2011b). Therefore, the work rates of the current sample are in fact underestimated in our calculations. It can be assumed then, that BATEX appropriately induced a work rate comparable to one-day international cricket. This work rate placed significant demands on the musculoskeletal and physiological systems of schoolboy and academy batters, inducing large changes in sprint performance over time ($p<0.05$; $d>0.8$).

7.3.1 Sprint Performance

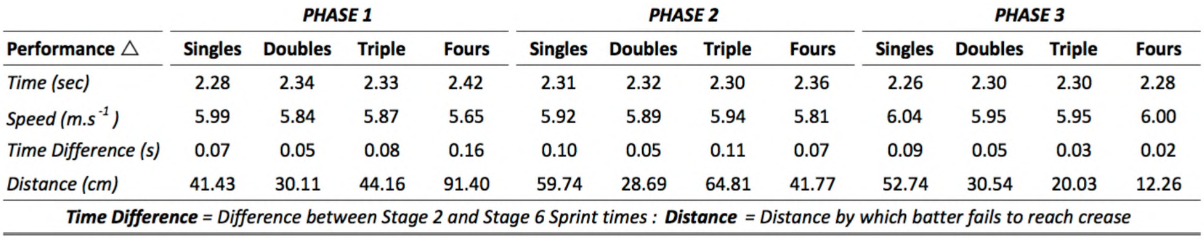
Sprint times slowed over time in schoolboy and academy batters ($p<0.01$) with the largest deteriorations observed in the final stage of each protocol (schoolboy; $d = 0.84$ and academy *test*; $d = 0.70$). Previous studies that implemented BATEX on different samples have reported similar changes in sprint performance (Houghton et al., 2011a; Pote & Christie, 2015). In addition, decrements in sprint times have also been reported in short-duration batting studies (Christie, et al., 2016) intermittent soccer research (Zois et al., 2011) and in studies on intermittent shuttle running (Morris et al., 2010). In high-grade and low grade Club cricketers, Houghton and colleagues observed a decrement in 5-0-5 m turn time ($p<0.05$) between stage 2 and 6 (2.19 and 3.02%, respectively). Similarly, Pote and Christie demonstrated a 3.57% slowing in the sprint times of University batters, over the same period. The decrements in sprint times in the current study are similar (schoolboy's 4.79% and academy 4.16%), confirming the reliability of BATEX for this measure. While the different percentage decrements could be attributed to training status, it is also possible that intra-participant motivational differences could explain these discrepancies.

The present study is the first to assess batting-related sprint performance in a number of run denominations, and allows mean and individual sprint performance to be assessed. In the present results, academy batters obtained the fastest mean sprint times in all phases of testing, with the exception of schoolboy sprint times in stage 2 (Table LXII). Additionally, time-related sprint decrements were smaller for academy batters (-0.095 s) when compared with schoolboy batters (-0.108 s). These results indicate that academy batters were better conditioned to withstand the fatiguing effects of running between the wickets. Moreover, while both samples were appropriately conditioned, the improved sprint performance in academy batters highlights the importance of cricket-specific training. Interestingly, the sprint decrement within academy batters for the *retest* condition is less (-0.066 s) than in the *test* condition and may suggest a pacing effect during *retest*. In spite of this, no *condition effects* were observed in mean sprint times between *test* and *retest* in academy batters.

These decrements suggest that; (i) the muscular demands imposed by BATEX exceeded the capabilities of the current cohort of batters, or (ii) batters down-regulated muscular workload to protect themselves to ensure that the innings was completed safely and successfully.

As seen in Table LXXIII the reductions in sprint times between stages have large implications for running between-the-wickets. The distance row indicates the average distance by which a batter will fail to cover their ground in the event of a run. When a batter fails to cover their ground and does not reach the crease before the ball hits the stumps, the batter will lose their wicket by way of a run out.

Table LXXIII: Changes in sprint times and sprint speeds over time (stage 2 vs. 6) and the implication for distance covered.



	PHASE 1				***PHASE 2***				***PHASE 3***			
Performance △	**Singles**	**Doubles**	**Triple**	**Fours**	**Singles**	**Doubles**	**Triple**	**Fours**	**Singles**	**Doubles**	**Triple**	**Fours**
Time (sec)	2.28	2.34	2.33	2.42	2.31	2.32	2.30	2.36	2.26	2.30	2.30	2.28
Speed ($m.s^{-1}$)	5.99	5.84	5.87	5.65	5.92	5.89	5.94	5.81	6.04	5.95	5.95	6.00
Time Difference (s)	0.07	0.05	0.08	0.16	0.10	0.05	0.11	0.07	0.09	0.05	0.03	0.02
Distance (cm)	41.43	30.11	44.16	91.40	59.74	28.69	64.81	41.77	52.74	30.54	20.03	12.26

Time Difference *= Difference between Stage 2 and Stage 6 Sprint times :* ***Distance*** *= Distance by which batter fails to reach crease*

Therefore, the 0.07 s decrement in single shuttle time of schoolboys between stage 2 and 6 (column 1), corresponds to the batter being 41.4 cm short of their crease (distances were calculated by a derivative of the equations of motion: distance = speed x time). In cricket, this is a significant margin, where often millimetres are enough to result in run outs. The largest decrements in sprint performance from each phase were in fours for schoolboy batters (0.16 s; 91.4 cm), three's during academy *test* (0.11 s; 64.81 cm) and singles in academy *retest* (0.09 s; 52.7 cm). Table LXXIII also indicates that the largest decrements in sprint times for schoolboy and academy batters are consistently found in triple shuttle times. This decrement is most likely related to the longer distance needed to be covered and the increased physiological demand required in covering this distance. Lockie et al. (2012) contend that the changes in performance in a run-a-three are related to the deceleratory and acceleratory movements required in the turn. The authors demonstrate that the time taken to complete the second run is longest. This is due to the deceleration in the first turn, the reacceleration after the turn, and the declaration required for the second turn. While not directly assessed, this theory could explain the decrements observed in the triple shuttle times. The current results indicate that this run type and specifically correct turning technique should be coached in conditioning practice. If technique, strength and speed are improved, the distance decrement and the potential for run outs can be reduced.

The mechanism of decreased sprint times is most likely due to neuromuscular fatigue. Noakes & Durandt (2000) proposed a biomechanical model that claims eccentric muscle actions reduce the efficiency with which muscles perform. The cause of this reduced efficiency in batters is thought to be the high eccentric demands required when running between the wickets. Furthermore, this fatigue reduces the ability of the muscles to store and reuse elastic energy in the facilitation of movement, thus impairing sprint performance (Noakes & Durandt, 2000). The slower sprint times observed in the current investigation indirectly support the work of Marcora, Bosio, & de Morree (2008), who contend that eccentric muscle actions reduce the time to exhaustion. While time to exhaustion represented Marcora and colleagues' participants capacity to perform work, sprint times represent the work capacity of the batting cohort in the current study. Therefore, despite differences in exercise modality, the present results show that increasing eccentric workload also reduces the capacity to perform work (sprint performance) in a cohort of amateur batters. Eccentric strength is therefore paramount to reduce fatigue and maintain sprint performance during batting.

The difference in sprint times between singles and fours in schoolboy batters was unexpected, as a four essentially represents a single shuttle time. It is possible that the decrement in fours (particularly in schoolboys) is a result of slowed decision making by batters when deciding if the shot was beating the fielder and on its way to the boundary. It is hypothesised that reduced acceleration off the mark may have decreased sprint speed, thereby increasing average sprint time.

The faster sprint times measured in the *retest phase* were also observed in the test-retest study of Houghton et al. (2011). These authors suggest that in trial 2, batters were either more resistant to the fatiguing effects of BATEX or batters delayed the onset of fatigue. The current study agrees with this notion. It is possible that the knowledge gained in the *test* condition allowed batters to augment their running style in the *retest* session (i.e. to score runs more quickly in the beginning of the over and rest in the latter part of the over). As a result, batters were better able to maintain sprint times, while recording a reduced physiological load at the end of each over. This theory is supported by the lower heart rate responses and the improved *post-test* vertical jump heights during the *retest phase*.

7.3.2 Muscular Power (academy batters only)

Repeated shuttle running had no effect on SJ and CMJ heights ($p>0.05$), a result previously established in batting-related studies (Houghton et al., 2011b, Houghton & Dawson, 2012). These authors compared club and academy cricketers' jump performance after BATEX, demonstrating that both SJ and CMJ flight times of academy cricketers were unaffected ($p>0.05$) immediately post simulation (L Houghton & Dawson, 2012). In a different study, repeated shuttle running decreased the SJ height of club cricketers by 5.15% while CMJ height was improved (1.01%) (Houghton et al., 2011b). In the present study, the results are similar, where academy batters *post-test* SJ height in the *test* session decreased (0.42%) and CMJ height increased (0.20%). In contrast, the *post-test* improvement in CMJ and SJ (0.55 and 0.98%, respectively) in the *retest* academy session are contrary to previous findings (Houghton & Dawson, 2012; Houghton et al., 2011a). The only main effect in the current study was observed in jump type, showing that CMJ heights were consistently better ($p<0.05$) than SJ heights. Higher CMJ heights when compared to SJ height has been previously established in running (McGuigan et al., 2006), soccer (Robineau et al., 2012) and batting research (Houghton & Dawson, 2012; Houghton et al., 2011b). This finding indicates the effectiveness of the stretch-shortening cycle in force production. Furthermore, because the decrement in SJ height was not paralleled by a decrement in CMJ height, the eccentric utilisation ratio increased by 6.4% ($p=0.051$; $d=1.09$). This result indicates why the use of the eccentric utilisation ratio is at times, contentious (McGuigan et al., 2006).

The current study and those of Houghton and colleagues indicate that CMJ height is unaffected by prolonged batting. Thus, the ability of batters to temporarily store and use elastic energy seems unaffected by repeated shuttle running, debunking the hypothesis of Noakes & Durandt (2000). Thus, it is possible that the biomechanical model of fatigue is not an appropriate model to explain the reduced sprint performance in the present study. Conversely, while SJ and CMJ height are shown to be reliable indicators of eccentric fatigue in, rugby football, soccer and hockey research (Markovic et al., 2004; McGuigan et al., 2006), their applicability to batting-related performance may be questionable. Also, the efficacy of BATEX in imposing high eccentric loads could be questioned. Future investigations should compare results from vertical jump tests to those of isokinetic dynamometry to elucidate their applicability in assessing batting-related eccentric fatigue.

The findings of Houghton and colleagues suggest that changes in jump height are linked to training status, where academy batters demonstrated no change in jump characteristics while club cricketers did. Cometti et al. (2001) confirm this theory, showing elite soccer players attain higher jump heights compared to sub-elite and amateur players. Once again the importance of training status is exemplified. It is, however, possible that academy batters paced themselves during BATEX, not producing an all-out effort. Indirectly then, batters could have prevented neuromuscular fatigue by manipulating (slowing) sprint times. Consequently, the slower sprint times could be the result of reduced motivation and/or a strategy to delay fatigue; explaining the lack of change in jump height and the *post-test* improvement observed in the academy *retest* session. It is probable that reduced 'motivation' may not occur in competition, where batters will very likely perform maximally to avoid the chance of being run out. This is no doubt a limitation of the current protocol, where extrinsic and intrinsic motivation may have been insufficient to produce maximal performance. Future studies should consider such limitations.

The improved vertical jump heights during *retest* (*pre* and *post-test*) when compared to the *test* condition ($p>0.05$) could be explained by either; (i) a habituation effect, (ii) performance regulation by batters, or (iii) as improved training status between *test* and *retest* sessions. It is possible that the repeated nature of experimentation allowed batters to become accustomed to the demands of the protocol and the techniques required for each jump. While the familiarisation session included habituation to the jump procedures, it is possible that players may have only perfected their technique in the final session. Furthermore, with the *retest* session taking place approximately 10 days after the *test* session, and with batters in their pre-season training regimen; there is a small possibility that training status may have improved between sessions.

7.3.3 Batting Accuracy (schoolboy batters only)

The batting accuracy of schoolboy batters improved over time, with batters increasing the proximity of the ball to the centre of the bat ($p>0.05$). Similar results have been established in our laboratory (Pote, 2013). Pote had amateur university cricketers complete the BATEX simulation and reported improved ($p<0.05$) batting accuracy over time. Additionally, Houghton and colleagues (2011a) found that the percentage of good bat-ball contacts improved ($p>0.05$) until the 25th over, whereafter a small reduction was observed. Noteworthy, the additional breaks in the present study means that the overall work rate in Pote's and Houghton's studies would have been higher. As such, even at higher work rates, batting accuracy is unaffected by prolonged batting.

Given the decrements observed in visual attention, psychomotor functioning, working memory and executive functions in schoolboy batters, the improved batting accuracy was unexpected. What this does indicate, is that despite slowing of processing speeds and reduced cognitive accuracy, batters are still able to perform well and hit the ball from the middle of the bat. As proposed earlier, this may indicate that the seated cognitive test battery may not provide a completely accurate representation of cognitive performance in response to batting.

Sarpeshkar & Mann (2011) contend that ball interception is a combination of predictive and prospective control, where the former is an autonomous control and the latter a control that requires real time information updating. The current batting accuracy measure provides instantaneous assessment of executive processing where the improvements suggest that performance was moderately improved ($p>0.05$; $d = 0.63$) with prolonged batting. Therefore, this measure could indicate, that the semi-autonomous processes of batting (predictive control) are not impaired during and after prolonged batting. Conversely, the seated cognitive results could suggest that the more effortful top-down processes required in batting may be more susceptible to impairment.

While measures of batting accuracy are important, the cross sectional assessment of batting accuracy may not be fully representative of batting performance over time. Therefore, future studies should consider measuring instantaneous and progressive batting accuracy in response to prolonged batting. This could be attained by implementing the present accuracy tool, in conjunction with the percentage of good and bad bat-ball contacts. Such additions may improve the reliability of this measure and provide a more holistic view of batting performance.

7.4 Physiological Responses

7.4.1 Heart Rate

The increase in heart rate over time ($p<0.05$) is supported in both short- (Christie, Todd, & King, 2008; Vickery, et al., 2013 Christie & Pote, 2014; Vickery, Dascombe, & Duffield, 2014) and long-duration batting studies (Houghton et al., 2011a; Pote & Christie, 2015). Mean heart rates observed in schoolboy (141 ± 19 bt.min^{-1}) and academy batters (*test*: 139 ± 15 and *retest* 132 ± 16 bt.min^{-1}) are similar to previous studies (Houghton et al. (2011b) - 141 ± 19 bt.min^{-1}; Pote & Christie (2015) - 144 ± 15 bt.min^{-1}) as are the stage-related changes. As a percentage of maximum, heart rate increased over time and was highest in the high-intensity phases of batting, confirming the intensity-dependent nature of batting established by Petersen et al. (2010).

Similar batting workloads have been reported in previous studies, with short duration high-intensity protocols eliciting the highest response to batting (Christie et al., 2008; Pote, 2013; Vickery et al., 2013a; 2013b). Comparing *in situ* heart rates between competition formats, Vickery et al. (2014) found that mean exercising heart rates were at 81% of age-predicted maximum during one-day games. Furthermore, batters spent approximately 63% of their time above 75% of age-predicted heart rate maximum. The current data indicate a lower physiological load, where work rate averaged 69% in schoolboys and 66% in academy batters. Furthermore, in schoolboy batters and in the academy *test* session batters' heart rates were only above 75% in the final BATEX stage, whereas they were not ever above 75% in the *retest* session (Table LX). These trends are supported by both Houghton et al. (2011a) and Pote & Christie (2015) who reported work rates of 71% and 73%, with batters only above 75% in the final stage of each study. Work rates per over indicate that schoolboy batters exercised above 75% for 23 min 20 sec- 19% of the total BATEX duration (126 min). In contrast, academy batters exercised above 75% for 11 min and 40 sec in the *test* session and 8 min 45 sec during *retest* (9 and 7%, respectively). It is possible then, that the workloads and intensities of BATEX should be revisited and matched to modern day batting loads and intensities. This will be discussed further in section 7.7.1

Despite lower reference heart rates (65 ± 10 vs. 70 ± 8 bt.min^{-1}), the exercising heart rates of schoolboy batters were consistently higher than academy batters. Higher exercising heart rates were also reported in lower-grade (compared to higher grade) batters in the BATEX simulation of Houghton et al. (2011a). As previously mentioned, the most notable physiological adaptations of improved training status are lower resting and exercising heart rates and improved recovery rates (Baechle & Earle, 2008; Daanen et al., 2012). As such academy batters were of higher training status. Furthermore, the experimental setup of the schoolboy batters (which included two additional cognitive test batteries) means that these batters had longer non-active recovery periods and a lower work-to-rest ratio- confirming the previous statement. With lower reference heart rates measured in schoolboy batters, the result suggests that reference heart rate may not always be the best indicator of training status. Additionally, the benefits of cricket-specific physical conditioning are demonstrated in these findings.

7.4.2 Fluid Balance and Sweat Loss

The reduction ($p<0.05$) in body mass and the corresponding fluid loss are consistent with those previously reported during BATEX (L Houghton & Dawson, 2012; Pote, 2013). Mean sweat loss of schoolboys (1.3% BM) was similar to the amateur sample of Pote (2013), who lost 1.8% BM during the 2hr 20min simulation. These findings illustrate the high physiological load imposed by BATEX and the reliability of the protocol for this measure. The magnitude of sweat loss does, however, appear to be sample dependent, where mean sweat rates of 0.8 ± 0.2 $L.h^{-1}$(Houghton et al., 2011a) and 0.9 ± 0.2 $L.h^{-1}$ (L Houghton & Dawson, 2012) have been reported in club cricketers and rates of 0.6 ± 0.2 $L.h^{-1}$ recorded in amateur batters (Pote, 2013). Mean sweat rate in the present results were lower (0.35 $L.h^{-1}$) than those previously reported in response to BATEX (0.6 - 0.9 $L.h^{-1}$). Furthermore, the sweat rates in the current study were higher for the schoolboy sample when compared to academy batters. The present sweat rates are also lower than those reported after short duration high-intensity batting (1.05 $L.h^{-1}$ - King et al., 2002) and during competition (0.5 - 0.6 $L.h^{-1}$ - Gore et al., 1994). Two factors could have produced lower sweat rates in the current study; (i) the lower work-to-rest ratio of the augmented BATEX design, and (ii) the temperature-controlled laboratory environment (23°C). The sweat rates of the current cohort are similar to the 0.5 ± 0.1 $L.h^{-1}$ observed during cool days (22.6°C) of competition (Gore et al., 1994). Comparison to the 0.6 ± 0.1 $L.h^{-1}$ observed on warm competition days (32.9°C) exemplifies the environmental implications on batters, where higher temperatures reduce the bodies thermoregulatory control (Hillyer, Menon, & Singh, 2015). Secondly, the longer duration of the current BATEX simulation, reduced the work rate of batters and as such, the sweat rate was reduced in comparison to that observed previously (Houghton et al., 2011a; Houghton & Dawson, 2012; Pote, 2013).

Importantly, the *ad libitum* water consumption of academy batters could explain the discrepancies in fluid loss between cohorts, and between previous investigations. During *test*, academy batters consumed an average of 1.1 L of water at 0.3 $L.h^{-1}$ whereas water consumption during *retest* was lower (1.0 L at 0.3 $L.h^{-1}$). Total substrate consumption of the schoolboy batters was 250ml of an isotonic sports drink. The additional fluid intake during *test* and compared to schoolboy batters would, therefore, increase *post-test* body mass and hence the fluid balance calculations. While schoolboys lost more body mass throughout the simulation, the rate of sweat loss was similar between samples (0.34 vs. 0.36 $L.h^{-1}$). According to previous exercise studies, the larger reduction of body mass in schoolboy batters (0.97 kg or 1.27% BM) when compared to academy batters (0.58 kg 0.75% BM), could explain cognitive impairment (Carrasco, 2008; D'Anci et al., 2009; Ganio et al., 2011; Smith, Newell, & Baker, 2012; Hillyer et al., 2015). Exercise that induces a mean loss of ≥1% BM significantly increases cognitive impairment (Neave et al., 2004; Ganio et al., 2011). Additionally, exercise with an intensity or duration that imposes body mass reductions > 2% has even larger decrements in cognitive performance (Carrasco, 2008; D'Anci et al., 2009; Smith, Newell, & Baker, 2012; Hillyer et al., 2015).

Specifically, forty minutes of treadmill walking (reduction of ≥1% BM) impaired vigilance ($p<0.05$) and visual working memory response latency ($p<0.03$) (Ganio et al., 2011). Similarly, Neave and colleagues (2004) reported significant impairment of cognitive performance when batters lost 0.8% BM during 30 min of high-intensity batting. In golf, cognitive impairment coincides with dehydration-induced body mass reduction of 1-2% (Smith et al., 2012). It is then safe to say, that dehydration of the schoolboy sample was an implicating factor that lead to cognitive impairments in executive function, vigilance and attention and working memory. Therefore, coaches and trainers should ensure that prolonged batting does not result in reductions in body mass equal to, or above 1%. Future studies should look to compare hydration rates and sweat rates between different calibre batters, so that a ceiling level of dehydration-induced cognitive impairment can be established.

While it may be considered a limitation of the current methodology, the carbohydrate solution consumed by schoolboy batters after the third cognitive assessment seems to have improved cognitive performance in the *detection*, *identification* and *maze* tasks during assessment 4. Research indicates that carbohydrates comprised mainly of glucose can be oxidised at a rate of 60 $g.h^{-1}$ (Jeukendrup, 2007). Approximately 40 min after ingestion the 39 g of carbohydrates consumed would have been oxidised. This time frame coincides with assessment 4 and could potentially explain the performance improvements mentioned. This is consistent with previous literature, where carbohydrate consumption during exercise improved cognition following 100 min of constant workload running at lactate threshold (Collardeau et al., 2001). These authors found that choice-response time in the experimental condition was improved ($p<0.05$) *post-protocol*, but in the exercise only condition, performance was unchanged. These data show the benefits of carbohydrate ingestion during prolonged exercise, both at constant and intermittent work rates.

7.5 Perceptual Responses

The linear increase in central and local perceived exertion are in agreement with previous cycling (Presland, Dowson, & Cairns, 2005; Crewe, Tucker, & Noakes, 2008) and batting studies (Christie et al., 2008; Christie & Pote, 2014; Pote & Christie, 2015). In the present study, the increases in perceived exertion were similar in both schoolboy and academy batters, however, schoolboy batters demonstrated stronger linear relationships with time (central: $r^2 = 0.94$ vs. 0.86; local: $r^2 = 0.97$ vs. 0.94). In addition, batters accurately perceived effort to be higher ($p<0.05$) in the maximal intensity stages when compared to the self-paced stages. These findings affirm those from other batting studies that have shown perceived exertion to be intensity- and duration-dependent (Christie et al., 2008; Sheppard, 2011; Elliott, 2014; Christie & Pote, 2014; Pote & Christie, 2015). The strength of the correlations between central RPE and exercising heart rate (Table LXIII), indicate that batters understood the rating scale and could accurately rate their cardiovascular effort. The weaker correlations observed in stages 1-4 (where batters underrated their physiological strain) suggest that batters were neither cognisant of the immediate rise in heart rate, nor the extent of this increase.

Sample-related differences do, however, indicate that academy batters were more accurate at rating the initial increase in heart rates and perhaps that they are better attuned to how their bodies responded to the simulation. While the initial rates of increase in perceived effort were higher in academy batters, the rate of change (relative to schoolboy batters) in the first 15 overs was lower in this sample. This was also the case when comparing rate of increase in RPE between overs 16-30 and overs 26-30. In line with literature on fixed work rate exercise, the higher initial perceptions of effort in academy batters (*test*), compared with schoolboy responses, should lead to earlier and greater performance decrements (Presland et al., 2005; Crewe et al., 2008; Marcora & Staiano, 2010). This was not the case, where in comparison to schoolboy batters, academy batters had lower exercising heart rates, faster sprint times and lower overall perceived exertion. With the higher initial rate of increase in perceived effort and the improved performance in academy batters (relative to schoolboy batters), it is possible that the mechanisms of fatigue in fixed work rate activity may not directly apply to intermittent batting. Based on the early work of Ulmer (1996), numerous investigators have provided substantial evidence linking perceptions of effort to performance regulation in endurance exercise (Baden et al., 2005; Crewe et al., 2008; Marcora, 2008; Tucker, 2009; Tucker & Noakes, 2009; Marcora & Staiano, 2010; Micklewright, Papadopoulou, Swart, & Noakes, 2010; de Koning et al., 2011; Smits, Pepping, & Hettinga, 2014). The application of these theories to intermittent exercise is less clear.

The model of teleoanticipation (Ulmer, 1996) and anticipatory regulation (Tucker, 2009) contend that performance is regulated in a feedforward manner, where physical performance will be optimal if conscious RPE does not exceed template RPE. However, when the requirements of the exercise bout are unknown (as in the current situation), athletes place a greater reliance on subconscious afferent sensory feedback to regulate performance (Baden et al., 2005; Micklewright, et al.,2010). It is possible then, that the higher perceptions of effort of academy batters in the first 10 overs could have allowed these batters to better regulate their performance for the remainder of the simulation. This could potentially explain the superior performance of academy batters and the reduced perception of effort. When comparing samples, it is possible that the template RPE of schoolboy batters was set too low and the afferent feedback received while batting (particularly in the later stages) produced a situation where conscious RPE exceeded template RPE. According to the anticipatory feedback model, the volitional limit to exercise at a fixed work rate is when a maximal tolerable RPE is reached (Tucker, 2009). At this point the brain subconsciously down-regulates performance. In contrast, Pageaux (2014) contends that it is not central down-regulation that alters performance, but rather an athletes motivational state.

Therefore, when perception of effort reaches a level that is too high and motivation is insufficient, output is reduced so that the work bout can be safely completed. Either of these theories can then explain the larger reductions in sprint times and higher exercising heart rates in schoolboy batters. What this alludes to, is that performance deterioration in schoolboy batters could be the result of the manner in which these batters paced themselves during the simulation.

In contrast to the training status argument presented earlier, the higher exercising heart rates, reduced sprint times and higher perceptions of effort could suggest that schoolboy batters did not pace themselves as efficiently as the academy batters. This notion is supported in previous literature (Elliott, 2014). Implementing a repeated measures 7-over batting simulation, Elliott examined how skilled and less-skilled batters paced themselves in three trails (control, unknown and deceptive) that varied according to the information provided (i.e. the number of shuttles required). It was observed that less-skilled batters had significantly higher perceived exertion, slower sprint times and higher muscle activation in response to the unknown and deceptive trials. This was particularly true in the unknown trial. Elliott concluded that skilled batters paced themselves more efficiently throughout the simulation, and as a result performance was superior. It appears then, that the self-selected nature of batting requires continual focus and a well-planned pacing strategy. Furthermore, that the level of batting experience (time at the crease) is pivotal in performance regulation. The present results are similar to those of Elliott (2014) and add that pacing can directly influence cognitive performance. This argument is strengthened when *test-retest* data is considered.

Compared to the *test* session, academy batters perceived the *retest* session to induce lower muscular and cardiovascular demand. Additionally, heart rate, sprint times and jump heights were superior during *retest*. It appears then that the information gained from the *test* session, assisted academy batters in attaining improved performance in the *retest* session. This result supports previous studies that have demonstrated the importance of experience (prior knowledge) in optimal performance regulation (Tucker & Noakes, 2009; Micklewright et al., 2010; de Koning et al., 2011; Smits et al., 2014). Presumably then, without previous experience of the BATEX duration and intensities, it is likely that schoolboy batters, and less so, academy batters (in their *test* session) adopted an all-out pacing strategy where conscious RPE could have exceeded maximal tolerable RPE (Tucker, 2009). This is evident in the linear increase ($p<0.05$) in perceived effort over time and the reduced muscular responses obtained in these sessions. It could also explain the cognitive decrements observed in the schoolboy sample and the larger impairments (when compared to *retest*) observed in the academy *test* session. Evidently, prior experience gained from the *test* session (i.e. intensities required, knowledge of the endpoint and total demand of the simulation) allowed academy batters to alter their template RPE and the initial exercise intensities (pacing strategy). Accordingly, this produced a situation where exercising RPE did not exceed template RPE, a resource reserve existed and batters were better able to regulate performance (Tucker, 2009). This altered strategy is evidenced in;

(i) lower initial RPE,
(ii) lower rate of increase in RPE,
(iii) lower exercising heart rates,
(iv) the reduced sprint decrement, and
(v) improved *post-test* vertical jump heights in the *retest* session.

Such a pacing strategy can also explain the cognitive performance results obtained during *retest*. In conclusion, the application of the anticipatory regulation model is suitable to performance regulation during prolonged intermittent batting.

7.6 Test-Retest: Validity and Reliability of Results

To assess the *test-retest* reliability of the academy batters results, a one-way multivariate ANOVA (MANOVA) was conducted for each dependent variable. Importantly, no *condition effects* were attained between *test* and *retest* in any of the performance measures. The only *condition effects* were observed in mean heart rate (*retest:* was lower), changes in body mass (*retest:* lower) and PNN30 (*retest:* higher). Therefore, the experimental design tested in the current study produces results that are reliable and reproducible. This is similar to the results obtained by Houghton et al. (2011b) who also implemented the BATEX protocol in *a test-retest* hypothesis.

As previously discussed (7.5), the *condition effects* observed in mean heart rate, change in body mass and PNN30 could be the result of an altered pacing strategy of the academy batters in the *retest* session. The reduced heart rate and lower body mass loss, suggest that batters did not exercise at as high an intensity in the *retest* session when compared to *test*.

Subsequently this produced alterations in the following performance parameters (Table LVIII);

(i) improved *post-test* SJ and CMJ in the *retest* session (p>0.05),
(ii) smaller decrements in mean sprint times between stages 2 and 6 (p>0.05),
(iii) reduced perceptions of effort (p>0.05), and
(iv) improvements in *post-test* psychomotor function (p>0.05), visual attention (p>0.05) and executive functions (p>0.05).

While changes in pacing strategies could explain changes between sessions, it is also possible that physiological adaptation, resulting from improvements in training status, could explain these differences. At the time of experimentation, batters were in their pre-season phase of training, where training workload was increasing each week. Therefore, the increased training workload in the 10 days between experimental sessions may have allowed physiological adaptation; producing increases in strength, improvement in muscular power and improved cardiovascular efficiency (Tortora & Derrickson, 2005; McArdle, Katch, & Katch, 2006; Baechle & Earle, 2008). This could explain the reduced physiological load, faster sprint times and improved jump performance as well as the lower perceived effort in the *retest phase* of experimentation.

7.7 Integrated Discussion

With a plethora of knowledge indicating the beneficial effects of physical activity on cognitive functioning (McMorris & Graydon, 1997; Netz et al., 2005; Angevaren et al., 2008; Lambourne & Tomporowski, 2010; Yanagisawa et al., 2010; Diamond, 2015) it was expected that batting activity would improve cognitive function in amateur batters. This was not the case and suggests that the cognitive requirements of batting mitigate the beneficial effects of a purely physical activity on cognitive functioning. Our data support previous findings that show cognitive improvement to be training status dependent (Budde et al., 2012; Casanova et al., 2013; Bullock & Giesbrecht, 2014), where prolonged batting facilitated cognitive performance domains in higher-trained academy batters, but impaired performance (p<0.05) in less-trained batters. As evidenced in the executive function and memory tasks, the results of both samples confirm Audiffren's 2009 theory; where exercise impairs performance to a greater extent in tasks that are, (i) controlled through top-down processing, and (ii) require effortful, explicit or consciously driven attention. By contrast, simpler tasks in the present study, that were characterised by autonomous bottom-up processing did not reveal decrements in performance, providing further support for Audiffren (2009).

Prolonged batting did not change processing speeds of schoolboy and academy batters statistically ($p>0.05$), however, Cohens *d* demonstrated small (d = 0.2-0.49) and moderate (d = 0.5-0.79) impairments in processing speeds and response accuracy of schoolboy batters only (Table LXXI). These impairments in information processing speed and accuracy were first observed at an intensity of 64%HR_{max}. At the same stage of assessment, academy batters were exercising at 64.3 %HR_{max}, however, cognitive performance was facilitated. In the final 15 overs, exercise intensity increased to 77.4 %HR_{max} in schoolboy batters, resultantly larger impairments were demonstrated. By contrast, the final 15 overs elicited a similar demand (76.9 %HR_{max}) in academy batters who were able to maintain performance. According to previous ACSM guidelines, these exercise intensities correspond to just over 50 and 60 %VO_{2max} (Lounana et al., 2007). Therefore, the intensity-related changes in cognitive performance of the present investigation are different to previous studies. At similar intensities, acute bouts of exercise have facilitative effects on cognitive performance (Chmura et al., 1998; Davranche & Audiffren, 2004; Davranche et al., 2005; Chang et al., 2011; Ashnagar et al., 2014). Similarly, prolonged exercise at these intensities also promote cognitive functioning (Collardeau, Brisswalter, & Audiffren, 2001; Collardeau et al., 2001; Serwah & Marino, 2006; Greig et al., 2007). However, as stated earlier almost all of these results were produced in purely physical tasks that did not possess the same cognitive demand inherent in prolonged batting.

This study shows that when exercise duration is prolonged and when the exercise modality requires added cognitive workload, the resultant effects on cognitive performance are not the same as acute bouts of activity where the modality is purely physical. In addition, the results indicate that the magnitude of performance change is mediated by individual differences in a batters age, playing experience, physical fitness and level of hydration. In light of this, the following theories are used to elucidate changes in cognitive performance;

(i) arousal theory,
(ii) resource theory,
(iii) effort-regulation,
(iv) neuroendocrinology theory, and

(v) the reticular-activating hypofrontality model.

The intensity-dependent effect of batting on cognitive performance is consistent with previous investigations (Lambourne & Tomporowski, 2010; Smith et al., 2010; McMorris et al., 2011 Chang et al., 2012). The theory most commonly employed to explain these changes is the inverted U-shaped function of arousal (Yerkes & Dodson, 1908). Arousal theorists predict that where an increase in task demands change physiological arousal, the allocation of mental resources changes accordingly (Kahneman, 1973; Sarter, Givens, & Bruno, 2001; Wickens, 2008). As such, arousal theory and resource theory are inherently linked. The theories state that when task demands (in this case, prolonged batting) are moderate and arousal is increased, cognitive performance can be improved. Conversely, when arousal is not optimal (i.e. too high or too low) performance deteriorates. The present heart rate and heart rate variability data show that the increased sympathetic activation (64.3 $\%HR_{max}$) in the first 15 overs was near optimal for academy batters and cognitive performance was improved. In schoolboy batters, the same intensity produced a situation where arousal (64 $\%HR_{max}$) was too high and resultantly, performance was impaired. The increasing intensity in the final 15 overs of batting induced higher levels of arousal and the decrements in cognitive performance observed *post-test* were larger. By contrast, while the *post-test* arousal of academy batters was also higher, this intensity appears closer to optimal than that of schoolboy batters, which allowed academy batters to better maintain cognitive performance. It appears for schoolboy batters that optimal performance was attained after five overs of batting when the relative intensity was 60.8 $\%HR_{max}$.

According to the neuroendocrinology theory of McMorris (2009), the improvements in cognitive performance after five and fifteen overs (schoolboy and academy batters, respectively) could be attributed to increases in circulating catecholamine concentrations. Subsequent increases in intensity then induce a state of over-arousal and hyperactivity of the limbic system. This in turn increases neural noise and reduces the efficiency of signal transduction to the effectors, potentially impairing the speed and accuracy of responses (McMorris et al., 2011). It is important to bear in mind that this theory has not been applied to prolonged exercise however, its application could explain the reduced response accuracy in the working memory and executive function of schoolboy batters.

The impairment in cognitive performance of schoolboy batters can also be explained by a reduction in resource availability. Resource theory contends that when task demands increase, physiological mechanisms produce an increase in the supply of resources; however, when demands are too high and resource supply insufficient, performance deteriorates (Kahneman, 1973; Wickens, 2002). It is possible that over the course of the simulation the increasing muscular and cardiovascular demands in conjunction with the cognitive demands of prolonged batting reduced resource availability. Dietrich, (2009) contends that reduced resource availability produces a scenario where the remaining resources are redistributed to brain areas that are in immediate need of these (Reticular-Activating Hypofrontality Model). This likely would have resulted in insufficient resources when performing the cognitive tasks. The increased magnitude of impairment in *post-test* visual attention, working memory and executive function could then potentially be the result of resource depletion, where the little recourses available were mobilised for cognitive performance. The larger impairments observed in executive functioning and memory also support Dietrich's hierarchical component of resource removal (Dietrich & Audiffren, 2011). Conversely, the relative demand of batting for academy batters was less, requiring fewer resources to fulfil batting activity. Sufficient resources were then available during cognitive assessment and resultantly cognitive performance was not impaired.

Importantly, without the measurement of blood and urine biomarkers or brain activation, caution in the application of Dietrich & Audiffren's (2011) and McMorris' (2009) models to the current context must be applied. While it is likely that such connections exist between these models and prolonged batting activity, future studies should apply these additional measures to confirm this.

According to non-exercising heart rate variability data, the decline in the heart rate variability between test batteries suggests that cognitive workload increased over time (Hjortskov et al., 2004; Taelman et al., 2011; Mukherjee et al., 2011; Mateo, et al., 2012; Luque-Casado et al., 2013; Cinaz et al., 2013). With further interpretation of this theory, results indicate that overall effort invested during cognitive assessment was highest *post-test* (increased effort regulation). It appears then, that with increasing physical demand, batters increased selective attention, affording greater effort to the final test battery. This is consistent with the contention of DiDomenico & Nussbaum (2011), who state that when physical exertion is high participants increase the allocation of resources to cognitive tasks. This strategy delays cognitive degradation, despite increased physical demand, and reduces the performance decrement over time. Such a strategy has been termed effort regulation or compensatory control, and is consistent in cognitive energetics literature (Kahneman, 1973; Robert & Hockey, 1997; Young & Stanton, 2002b). However, these data must be interpreted with caution because the changes in heart rate variability between batteries are likely, in most part, an exercise effect (Kamath et al., 1991; Javorka et al., 2002; Peçanha et al., 2013).

While cognitive performance of academy batters improved with increased effort, schoolboy batters cognitive performance was impaired; this despite similar increases in effort regulation. This lends further support to resource depletion in schoolboy batters, but also suggests that the strategy of task completion could have been different between samples. An example of this is explained in the self-regulatory failure contention of Vohs & Heatherton (2000). Moreover, when the state of active effort (which is required to control behaviour in one domain) increases, it can lead to diminished capacity for self-regulation in other domains. This is similar to the dual task interference concept in multiple resources theory (Wickens, 2002, 2008). Relatedly, it is possible that schoolboy batters focused a greater deal of attention on the self-regulation of speed of processing, resulting in reductions in accuracy. Bogacz et al. (2010) more commonly refer to this as a speed-accuracy trade-off, where one aspect of task performance is maintained at the expense of the other. Such a strategy is witnessed when comparing the processing speeds between samples. Schoolboy batters, while faster than academy batters in all tasks and at all assessment points, were also less accurate than academy batters. Therefore, the desire to complete the tasks as quickly as possible may have caused the accuracy impairments observed in the *maze* and *one-back* tasks. The more risky strategy of increasing speed could have large performance implications in competition, where accuracy in batting is paramount.

By contrast, differences in effort regulation between tasks could also account for the changes in cognitive performance over time. The discrepancy in the post-exercise modulation of heart rate between the present results and those previously reported (Javorka et al., 2002; Kamath et al., 1991), suggest that the cognitive test battery altered post-exercise autonomic modulation. Therefore, changes in heart rate variability between tasks could be attributed to the differential demands of the individual tasks. In schoolboy batters, the consistent time-related increase in heart rate variability parameters show that these responses were not sensitive to the differential effects of each task. Accordingly, this shows (compared to academy batters) continual decrease in cognitive workload and, perhaps, that schoolboy batters became task averse with time (i.e. they withdrew selective attention). Conversely, the *post-test* fluctuations in both frequency spectra and time domain parameters of academy batters, indicate differential workloads between tasks. This details a more pronounced regulation of attention and that academy batters were not task averse during *post-test* cognitive assessments. These differences in attentional control could account for the larger impairments observed in schoolboy batters. Therefore, a likely explanation for the *post-test* cognitive impairment (reduction in academy batters), could be related to motivation and the willingness to allocate effort after a physically demanding batting period. It is possible that this scenario may not occur in competition, where motivation will be both intrinsic (the desire to score runs) and extrinsic (fighting for a place in the starting line-up). To avoid such a situation in future, researches should try to maximise extrinsic player motivation which would then increase ecological validity.

That said, a limitation in the interpretation of the effort-regulation hypothesis, is the influence of batting activity on heart rate variability stationarity (Jorna, 1992; Trimmel et al., 2015). The majority of traditional research was conducted in conditions where physical activity was not required and where stationarity was high. The addition of physical activity in the present study and the corresponding cardio acceleration and deceleration that occurs before and after exercise evidently has an effect on heart rate data. Notwithstanding, the task related changes indicate that heart rate variability is sensitive to changes in workload despite the reduced stationarity. Importantly, a measure of effort-regulation more appropriate in the concurrent assessment of batting-related cognitive performance has not yet been established and as such, consideration of these findings should assist future experimental design. Once wireless EEG devices become more robust against physical activity and the time taken to complete EEG assessments is reduced, this could then become an appropriate tool for measuring cognitive performance and effort-regulation while batting. Other considerations for the assessment of heart rate variability are presented in the subsequent section (7.8).

Physical performance responses provide support for the resource depletion argument presented earlier. The reduction in sprint times could indicate that there were insufficient metabolic resources to fuel muscular contraction and hence maintain sprint times. In schoolboy and academy batters, the slower sprint times and elevated physiological responses suggest batters are fatigued. However, when vertical jump heights are considered *post-test*, these suggest muscular power is not impaired and perhaps academy batters were not fatigued. Furthermore, the improved jump height and reduced sprint decrement in the academy *retest* session suggest that performance regulation had changed all together.

It is plausible then, that the demands inherent in BATEX were insufficient to induce a state of fatigue in academy batters. Conversely, these demands were too high for schoolboy batters and consequently cognitive impairment was observed. The differences in sprint times and cognitive performance between samples could thus be a resultant difference in pacing strategies adopted by batters. While it is possible that schoolboy batters adopted an all-out pacing strategy, the more experienced academy batters appear to have adopted a strategy that aimed to preserve energy and to ensure completion of the protocol. This is especially true in the *retest* session, where the afforded information gained from the *test* session undoubtedly affected the manner in which academy batters completed BATEX.

Alternatively, physical performance decrements could be explained by failure of aerobic energy systems to supply ATP to the required muscles. While the intermittent profile of BATEX would tax all energy systems, the prolonged duration would require energy supply that predominated through aerobic metabolism. Additionally, the frequent 35 second rest periods would promote ATP replenishment via the phosphocreatine system and fast glycolysis (Baechle & Earle, 2008). In further support, muscular power *post-protocol* and single and double shuttle sprint performance between stages 4 and 6 were unaffected. Each of these were performed in under eight seconds, demanding ATP by anaerobic metabolism (Gastin, 2001; Baechle & Earle, 2008). Therefore, these energy systems seem not to be fatigued by prolonged intermittent activity. Triple shuttle time was slower ($p<.05$) in stages 6 compared to stage 4. Accordingly, fatigue experienced when running a triple shuttle would most likely be explained by the failure of aerobic metabolism or by a voluntary reduction in muscle recruitment. RPE results support this claim, where participants' perception of fatigue was highest in stage 6. It is likely then, that 'fatigue' can be best explained by the psychobiological model of performance (Pageaux, 2014) where physical performance changes were likely the result of reduced motivation and physical effort during batting. Contradicting this is the increased effort regulation during cognitive assessment. However, when considered with the *time-on-task effect*, the reduction in mental effort over time may show that fatigue was present, and that batters could only remain focused for a certain portion of the battery. Hereafter, neuromuscular, cardiovascular and cognitive fatigue prevailed, promoting task aversion and reduced cognitive performance.

It is almost certain that reduced *post-test* cognitive performance in both cohorts is the result of over-arousal and additionally, that the larger decrements in cognitive impairment in schoolboy batters was the result of resource depletion. Several questions remain unanswered at present: (i) why were academy batters less susceptible to cognitive degradation? (ii) are the decrements observed between cohorts related to differences in training status, age (i.e. development), or experience? and (iii) was the workload of the batting simulation appropriate for academy batters?

The contrasting cognitive performance responses between schoolboy and academy batters suggest that the sample characteristics play a large role in tasks of this nature. The most notable differences between samples are the age and playing experience of participants. In line with previous literature, differences in age (schoolboy; 17 ± 0.9 years vs. academy; 19 ± 1.0 years) and hence development, could account for the discrepancies in cognitive function (Knapp & Morton, 2013). As previously stated, prefrontal cortex development could explain these changes (Sowell et al., 1999; Teffer & Semendeferi, 2012; Knapp & Morton, 2013). Therefore, when compared to academy batters it is possible that the structures required for executive control and working memory may be less developed in schoolboy batters: explaining the discrepancies in cognitive performance. Further support is demonstrated in the lack of differences between samples in the *detection* and *identification* tasks. These can be characterised as autonomous tasks that require bottom-up processing and as such are controlled by lower-order cognitive centres. Furthermore, complex tasks need more resources to activate the higher brain centres to maintain performance. Resultantly, the larger decrements experienced in higher-order tasks (*maze* and *one-back*) could be due to age-related development of pre-frontal cortex.

The longer playing experience of academy batters (5.81 ± 1.4 vs. 4.10 ± 1.0 years) and perhaps more exposure to competition and practice, could improve skill levels and batting experience. This collective term, 'experience' could also explain differences in physical and cognitive performance. This higher response accuracy observed in academy batters in the current cognitive tasks is indirectly supported in the occlusion studies of (Müller et al., 2006;

Mann et al., 2010). In these occlusion studies, skilled batters had improved response accuracy when predicting ball type. The results from occlusion studies and the present results allow the author to speculate that the visual systems of skilled batters are better attuned in early detection and utilisation of environmental stimuli, which promote better accuracy rates. Therefore, in the current setting, the higher-skilled academy batters may be better able to apply these skills in cognitive task performance resulting in smaller performance decrements. Stretch, Bartlett, & Davids (2000, p934) contend that, *"The limitations of the human information-processing system are typically not due to threshold properties of the performer's perceptual systems ... Rather, `software' factors have been implicated: extensive knowledge and skill in using the mental processes of perception, attention and memory underpin the inadequacy of the visual system"* This statement supports the continuing theme in the current discussion, where motivational factors and performance-regulation are likely mitigating in overall batting performance. Coupled to this, and as evidenced in section 7.5, the proposed manner in which academy batters paced themselves during the simulation can explain physical performance differences as well as differences in cognition.

Certainly a mitigating factor in performance differences is training status. As I have already touched on, improved fitness allows for a lower physiological load for the same relative workload. That said, over-arousal can explain differences in cognitive performance while reduced efficiency of aerobic and anaerobic metabolism could explain physical performance differences. Linked to this is the issue of hydration. While academy batters consumed water *ad libitum*, the restriction of substrate intake during BATEX is likely confounding on the physical and cognitive performance of schoolboy batters.

In response to the questions presented earlier; it does appear that the combination of age-related development, improved physiological functioning and better performance regulation can account for the differences between samples.

7.7.1 The Efficacy of BATEX: A Critical Reflection

The cardiovascular and muscular responses obtained in this series of investigations are similar to those previously reported (Houghton et al 2011a, 2011b; Houghton & Dawson, 2012;Pote, 2013; Pote & Christie, 2015). Thus the reliability of BATEX to induce similar workloads in amateur batters is again demonstrated. Further, the similarity in responses between schoolboy and academy batters and, also, the reliability between the *test* and *retest* phases further support this contention. What is apparent is that the workloads established presently and those reported elsewhere, are dissimilar to the one-day competition workloads recorded by Vickery et al. (2013a, 2014). While Houghton founded BATEX on time motion data from the 2003-2009 ICC World Cups and ICC World T20 Cups, it is possible now that BATEX may no longer be representative of modern day batting. From the present data it appears that the associated intensities of BATEX were not high enough to overload academy batters. Therefore, it seems probable that modern day training practices, where strength training and conditioning receive increased focus, better prepare batters for the associated demands of BATEX. As such, revision of these demands and intensities may be necessary.

According to ESPN Cricinfo (2016), modern day scoring rates for one-day internationals and T20 matches have changed and now represent higher team totals, faster run rates and a greater proportions of boundaries scored (Table LXXIV). Subsequently, the muscular and physiological demand placed on batters will have also changed. While scoring has increased, the relative proportion of boundaries to non-boundaries has also increased. This may then reduce the running requirements of batters and the associated physiological demands. In spite of this, it appears from the physiological data that BATEX under loaded academy batters (in comparison to Vickery and colleagues data) resulting in a reduced cardiovascular demand.

Table LXXIV: Run rates and scoring rates of modern day cricket in comparison to that used by Houghton and colleagues (2011) in the design of BATEX.

	Run Rate (runs/over)	**Strike Rate (runs/100 balls)**	**Bondaries (4's and 6's: %)**	**Non-Boundaries (%)**
Seasonal Differences				
2003-2009	4.50	74.9	45%	55%
2013-2016	5.08	84.7	48%	52%
Major Tournaments				
2003-2009	5.88	98.0	51%	49%
2013-2016	6.69	111	55%	45%

Houghton et al., (2011b, p 801) proposes that "*the simulated batting innings may be used to progress research on the physical fatigue demands of cricket batting*". While the simulation has been implemented effectively in a number of studies and its purpose has been achieved, future investigations should replicate the time motion methods used by Houghton to establish modern day work rates and intensities. Once this is done, the protocol should be restructured so that its use in research may continue.

7.7.2 Performance Regulation and Fatigue Mechanisms in Batting: A Proposal

In their book on exercise and cognition, McMorris, Tomporowski, & Audiffren (2009) conclude that the best way to explain the effects of acute exercise on cognitive performance is to use an interdisciplinary rationale. Likewise, the evidence from this study suggests that no single model of fatigue can explain performances changes in amateur batters. Rather, an inter-disciplinary rationale would be the best method to explain fatigue as a result of prolonged intermittent batting.

While this investigation has drawn on a number of theories within psychology, neuroscience, biomechanics and physiology to explain the performance changes observed. The author contends that; (i) the added cognitive component inherent in batting and the apparent cognitive fatigue in prolonged settings dictates a model that interprets fatigue at the level of the brain, (ii) the physical nature of batting requires explanation from a neuromuscular and physiological perspective and (iii) the self-paced nature of batting, where the outcome is often unknown, requires a model that focuses on self-regulation and motivation.

When considering cognitive control during batting, the intermittent fluctuations in arousal and the accompanying effects on cognitive performance are best explained by the concepts of arousal theory (Kahneman, 1973; Wickens & Hollands, 2000). Similarly, the neuroendocrinology theory takes the basis of arousal theory and places a substantive physiological underpinning to explain performance changes with optimal and suboptimal levels of arousal (McMorris, 2009). Second, in a prolonged setting, like in the current simulation, the effects of time-related fatigue are best conceptualised in resource theory, where reduced resource availability or depletion can significantly impair cognitive functioning. Support in this regard comes in the reticular-activating hypofrontality theory, where Dietrich (2009) provides insight into the manner in which resources are redistributed to maintain processing. Lastly, the self-paced nature of batting, particularly in competition, requires explanation from cognitive energetics (Robert & Hockey, 1997). In this regard, the inherently cognitive nature of batting needs to be regulated through selective top-down control.

The physical nature of batting and the repeated sprints between the wickets require batters to have efficient cardiovascular functioning and effective control of efferent output by the brain (Noakes, 2000). However, due to the intermittent nature of batting, physical fatigue cannot be explained by the traditional physiological models of exercise (the classic cardiovascular-anaerobic model, the energy supply-energy depletion model and the muscle recruitment model). This is mostly due to the low work-to-rest ratio, where often batters have periods of non-active recovery. Noakes & Durandt (2000) proposed that the best explanation for fatigue induced by batting was nested in the biomechanical model. However, this study has shown that the ability to store and reutilise elastic energy is not the leading cause of batting-related fatigue and subsequently the biomechanical model may not be applicable in the current setting. Perhaps more appropriate then, are the anticipatory regulation and psychobiological models. The self-paced nature of batting, where often the duration and intensity of the innings are unknown, requires continual feedback from the periphery and motivation to fulfil performance. In this regard, the continual updating of perceived exertion appears paramount in performance regulation and, therefore, the anticipatory model of performance regulation seems most appropriate in describing fatigue (Tucker, 2009). That said, the author agrees with the motivation aspects of the psychobiological model (Pageaux, 2014), where without sufficient motivation to continue exercising maximally, performance will be impaired.

7.8 Critical Reflection

While the objective of this study was to determine if prolonged batting impaired cognitive performance in a sample of amateur batters, the differences in performance between schoolboy and academy batters was unexpected. In hind sight, the age, playing experience and training status should have been more closely controlled. Future investigations should consider the implications of these individual differences and scrutinise the sample more carefully. However, while this finding was unanticipated, it provides novel information regarding cognitive impairment and performance regulation during prolonged batting. It is also possible the skill level of the school boy cohort may potentially be differential between First XI and Third XI teams. Future studies should try to close this gap if a similar school boy sample is utilised.

The use of a seated computer-based test battery appears to limit the specificity of batting-related cognitive performance. Furthermore, the limited perception-action coupling and time taken to conduct the test battery could have reduced the demand placed on batters and the ecological validity for batting. However, this tool is presently the best means of assessing cognitive performance as it is scientifically validated and sensitive to subtle changes in performance. Furthermore, the visually oriented nature of each task within this test battery appropriately taxes selective attention while each task imposes differential demands on central processing. A structural component of the current experimental design could also be seen as a limitation. Where previous exercise-related research assessed post-exercise cognitive performance once heart rates had returned to 10% of reference measures, the implementation of this criterion would have further reduced the demands of BATEX and subsequently, the validity of the results. Therefore, discrepancies attained in performance parameters between the current study and those previously reported could be the result of this methodological difference.

BATEX was a good tool for simulating a one-day match innings in the current cohort of batters. This is because it has strong perception-action coupling, high ecological validity, realistic physical demands and it applies appropriate cardiovascular strain on batters. However, the foundation of the protocol was for use in professional cricketers and not for amateur batters. Therefore, the use of this protocol for the current sample may be seen as a limitation in this study. Notwithstanding, the scientific validation of this protocol was the primary reason for its implementation as the independent test protocol and in the authors opinion outweighs the disadvantages of the potentially high workloads associated. In contrast, while the modern day game places a greater focus on strength and conditioning and where athletes are better conditioned to withstand the physical demands of batting, it appears that BATEX may need to be updated. The revision would need to ensure that the physical strain imposed conforms to that of current batting activity.

It is possible that the speed at which balls were projected from the bowling machine may have taxed the two samples differentially and could have potentially affected the cognitive demands placed on each cohort. In this regard, the ball speed (105 km.h^{-1}) may be interpreted as less challenging for the more experienced academy batters and resultantly the cognitive workload may have been reduced for this sample. Future investigations should perhaps utilise a faster bowling speed for more experienced samples.

A potential limitation in the measurement method of heart rate variability in the current study, is that physical activity undoubtedly influenced the stationarity of the data recorded; where the timeframe between batting and cognitive testing was too short (Jorna, 1992; Nickel & Nachreiner, 2003). Furthermore, the timeframe between tasks may have also been too short (~20 seconds). As such it may not have provided adequate time for heart rate and heart rate variability to stabilise, increasing positive and negative transfer between tasks (Nickel & Nachreiner, 2003). In light of this, the change in heart rate variability would have been reduced had a brief period of rest been taken between batting and the onset of cognitive assessment – as shown by Luft et al. (2009). However, additional time between tasks would have increased test battery length. This was not feasible as the already lengthily break from batting is uncharacteristic of competition. Notwithstanding, future heart rate variability studies should assesses this parameter in conjunction with spirometry and blood pressure. This will allow clarification of effects due to increases in parasympathetic modulation and baroreflex stimulation.

CHAPTER VIII - SUMMARY AND CONCLUSIONS

The aim of the current investigation was to determine if prolonged intermittent batting and the subsequent cardiovascular and muscular strain, impaired cognitive performance in amateur batters. From the current results, it does appear that prolonged intermittent batting impairs cognitive performance. However, the degree of impairment is most certainly related to a batters experience, training status and hydration levels. While this study did not aim to answer the question, "are cognitive performance changes dependent on individual differences?" it provides novel information in this regard. The results show that while cognitive performance was impaired by prolonged intermittent batting activity, the magnitude of this was larger in a younger, less experienced sample.

8.1 Summary of Procedures

A prolonged batting simulation that replicated the demands of scoring a one-day international century was used to induce batting-related fatigue of the physiological and musculoskeletal subsystems. Before, during and after the simulation, psychomotor function, visual attention, working memory, visual learning and memory as well as executive function were assessed (CogState brief test battery). During cognitive assessments, heart rate and heart rate variability parameters were sampled so that autonomic modulation of the heart could be determined. To establish physiological, physical and perceptual strain, inherent in the simulation; heart rate, perceived exertion and sprint time data were collected each over.

The investigation was divided into three smaller studies- *phase 1* (large-scale pilot), *2* and *3* (test-retest hypothesis). The methodological differences between *phase 1* and *phase 2* and *3*, were (respectively); the frequency of cognitive assessments (five vs. three) and in the sample used (schoolboy vs. academy batters). In terms of dependent variables, *phase 1* had the addition of batting accuracy only. In the early stages of *phase 2* the batting accuracy hardware was broken beyond repair, resultantly this variable was not included in *phase 2* and *3*. Rather, vertical jump height was added to assess muscular performance.

8.2 Summary of Results

In both schoolboy and academy batters, the prolonged batting session significantly increased heart rate ($p<0.01$;$d>0.8$) and perceived exertion ($p<0.01$;$d>0.8$) over time. Sprint times slowed significantly over time ($p<0.01$;$d = 0.84$ and $p<0.01$;$d = 0.70$) and vertical jump height was unaffected ($p>0.05$; $d<0.2$). The accuracy with which schoolboy batters hit the ball improved moderately between the first and the final over ($p>0.05$; $d = 0.63$). Reductions in body mass during the simulation were significant ($p<0.01$) in both samples, however, the magnitude of reduction was larger in schoolboy (1.27 %BM) compared to academy batters (0.75 %BM).

While cognitive performance demonstrated minor decrements over time in academy batters ($p>0.05$; $d<0.2$), the magnitude of impairment in psychomotor function ($p>0.05$; $d = 0.37$), visual attention ($p>0.05$; $d = 0.56$), working memory ($p>0.05$; $d = 0.61$) and executive function ($p>0.05$; $d = 0.58$) was larger in schoolboy batters. In both samples, the simulation altered the modulation of heart rate significantly. Heart rate variability decreased linearly with time spent batting ($p<0.01$; $d>0.8$). At the start of each cognitive test battery, heart rate variability was significantly reduced compared to *pre-test* levels. These measures showed steady increase with time-on-task, and were higher ($p<0.05$) in the last task of the battery compared to the first.

The results were replicated in the *retest phase* of this investigation, and only two *condition effects* were observed; (i) heart rate (*retest* lower: $p<0.04$;$d = 0.39$), (ii) body mass (*retest* lower: $p<0.03$;$d = 0.09$). Additionally, a task-related *condition effect* in heart rate variability - PNN30 was also observed (*retest* higher: $p<0.03$; d = not calculated). Therefore, the *test-retest* reliability of the method employed in *phase 2* and *3* was high.

8.3 Response to Hypotheses

Cognitive Performance

1. *The null hypothesis states:* that prolonged batting will have no effect on information processing in the following domains: psychomotor function, visual attention, visual learning and memory, attention and working memory and executive functions.

   Response: Differences were established over time for psychomotor function, visual attention, attention and working memory and executive function in schoolboy batters. Therefore the null hypothesis is rejected for these cognitive domains in this sample. The null hypothesis is tentatively accepted for cognitive performance in academy batters and for visual learning and memory in both samples.

2. *The null hypothesis states:* that prolonged batting will have no effect on time domain and frequency spectrum parameters. This hypothesis applies individually to each measure of heart rate variability.

   Response: Differences were established between over time assessments of time domain and frequency spectrum parameters in both schoolboy and academy batters. Therefore the null hypothesis is rejected.

3. *The null hypothesis states:* that the differential cognitive demands of each task will have no effect on heart rate variability parameters. This hypothesis applies individually to each measure of heart rate variability.

   Response: In both schoolboy and academy batters, differences were established between tasks for time domain parameters, therefore, the null hypothesis is rejected for these parameters. Isolated differences were established in frequency spectrum parameters of schoolboy and academy batters, therefore the null hypothesis is tentatively accepted for these parameters.

Batting Performance

4. *The null hypothesis states:* that prolonged batting will have no effect on sprint times.

   Response: Differences were established between over time for sprint times, therefore the null hypothesis is rejected.

5. *The null hypothesis states:* that prolonged batting will have no effect on vertical jump height.

   Response: No differences were established over time in vertical jump heights, therefore the null hypothesis is accepted.

6. *The null hypothesis states:* that prolonged batting will have no effect on batting accuracy.

Response: Differences in batting accuracy were established over time, therefore the null hypothesis is rejected.

Physiological Responses

7. *The null hypothesis states:* that the physiological responses of batters will remain unchanged throughout the simulation. This hypothesis applies individually to both heart rate and body mass.

   Response: Differences were established over time in heart rate and body mass, therefore the null hypothesis is rejected in both regards.

Perceptual Responses

8. *The null hypothesis states:* that the perceptual responses of batters will remain unchanged throughout the simulation. This hypothesis applies individually to both central and local ratings of perceived exertion.

   Response: Differences were established over time in central and local ratings of perceived exertion, therefore the null hypothesis is rejected in both regards.

Test-Retest

9. *The null hypothesis states:* that there will be no differences in cognitive performance, batting performance, physiological responses or perceptual responses between the *test* and *retest* sessions. This hypothesis applies to each dependent variable individually.

   Response: Differences were established between *test* and *retest* for mean heart rate, body mass and for a *task effect* of PNN30. Therefore, the null hypothesis is rejected for these responses. The null hypothesis is accepted for all other dependent variables measured in the *test* and *retest* sessions.

8.4 Future Recommendations

8.4.1 Research Directions

This study highlights a number of issues inherent in controlled cognitive assessment when the task and task environment are dynamic. A limitation in using the CogState test battery in a study on batting is that it removed batters from the batting environment, thereby reducing the specificity of the findings to batting. To truly understand the implications of prolonged batting on cognitive performance, future studies should design protocols that assess cognitive performance while batting. A potential measure of batting specific cognitive performance could combine contact mats, motion capture systems and measures of pre-motor time, initiation time and movement time to assess psychomotor function (Davranche et al.,2005; 2006; McMorris et al., 2005; Chang et al., 2009). Such a methodology could extend knowledge into the mechanisms of psychomotor performance, and whether or not fatigue is central or peripheral in nature. Additionally, eye-tracking could be used to assess visual performance of batters and if fatigue of the visual system (as measured by changes in saccade speed, blink frequency, fixation duration and pupil diameter) is the root cause of performance impairment. Unfortunately these methods were neither possible in the current laboratory nor within the means of our institution. To assess batting performance, percentage good and bad ball-contacts could be combined with target accuracy (hitting the ball through allocated zones). This will provide insight into batting skill and how this is affected by prolonged batting.

To determine the applicability of heart rate variability in assessing cognitive workload following physical activity, future investigations could replicate the current methods in a randomised control design. The comparison of heart rate variability indices between an exercising control group (no cognitive assessments) and an exercising experiment group (cognitive assessment following batting) could clarify the relationship between recovery heart rate variability and variability brought about by each cognitive task. Further, this would inform changes in cognitive performance due to fatigue or changes in cognitive workload and task aversion. The addition of spirometry during cognitive assessment could clarify the contribution of breathing frequency to changes in parasympathetic modulation. This would inform researchers whether autonomic modulation was due to cognitive task performance or to changes in respiratory sinus arrhythmia.

With regard to BATEX and its efficacy in inducing muscular fatigue, future studies should measure isokinetic strength before and after the simulation. This will provide a more accurate representation of the extent of muscular fatigue. Furthermore, changes between pre and post-test hamstring and quadriceps strength may facilitate understanding into the contributions of these musculatures to running. These measures could also provide insight into the mechanisms of physical fatigue, illustrating the applicability of the biomechanical model in describing batting-related fatigue. Future investigations can also look to reassess the workloads associated with BATEX and whether the current simulation is appropriate for modern day batting.

8.4.2 Practical Applications

Evidently improved training status results in a lesser decrement in cognitive performance. When relating this to cognitive energetics and performance regulation, for the same physiological load, a batter with a higher level of cardiovascular fitness would incur a lower level of arousal. Therefore, when operating at high-intensities, what would become over arousal in a less-fit individual will perhaps be a more optimal arousal in the higher-trained batter. Cognitive performance might then be less affected by that particular intensity. The current results show the importance of whole body strength and how strength is needed to withstand the physical demands required in batting. Academy batters demonstrated smaller decrements in sprint times and resultantly improved training status can offset the time-course of fatigue. The implications of such a decrement have been discussed and the potential for runouts alluded to. These findings demonstrate the importance of proper conditioning and training. Coaches should, therefore, place a larger focus on cricket-specific strength and conditioning as a method to deter cognitive decrement while batting and to reduce the chances of injury. Furthermore, training should incorporate cognitive training aspects (coping strategies, innings management/pacing, match debriefs) and could be implemented by coaches as a mechanism to reduce batting failure resulting from cognitive fatigue. This seems especially important at a developmental age (i.e. schoolboy level).

The possibility that cognitive impairment may be related to player experiences means that coaches and trainers should focus on developmental learning and skill acquisition from a young age. Coaching should consider the importance of both extrinsic and intrinsic motivation and how these can influence performance. Lastly, while performance regulation is highly individualised coaches should revisit competition performances and debrief players as to areas of improvement.

Cricket-specific conditioning should be the focus of conditioning at all levels of play (schoolboy and higher). The author proposes the following condition practices;

» From personal coaching experience and from exposure to the schoolboy and academy batters' (utilised in this study) practices, each batter's net-based practice is generally short in duration (approximately 5 overs). It is proposed that these durations are insufficient for developing cognitive abilities. Therefore, if coaches want their batters to improve cognitive abilities and to offset the cognitive impairment associated with prolonged batting, training must incorporate longer duration batting sessions.

» With the above in mind, training should consider reducing the amount of net-based training and develop a greater reliance on settings representative of competition. A means of doing this is to increase the proportion of centre-wicket training. The highest ecological validity in this regard will be attained by having live bowlers and fielders. However, this is often not viable, as player workload monitoring is paramount in fatigue and injury prevention. Furthermore, the feasibility of such practices are often limited by monetary and human resources and time constraints. Therefore, coaches could implement centre-wicket scenarios with a 30 yard netted-circle, where batters are required to hit balls (from multiple live bowlers or a machine) through allocated zones. If combined with running requirements the ecological validity and transferability to practice will be maximised. Such training at a schoolboy level will hold large potential for skill and player development. Once again, intervention studies could look to assess this.

» Training should also combine prolonged batting periods with high-intensity shuttle running. This will promote cardiovascular and muscular strain at practice which has the potential to accustom players to batting while in a fatigued state. Additionally, this could encourage batters to formulate decisions when fatigued and could teach batters correct turning techniques. This type of training can also allow batters to develop cognitive coping strategies. The author proposes that if this is done more frequently, this will increase the transferability of these skills to competition, perhaps reduce the cognitive load while at the crease. Future intervention studies could test such a hypothesis to identify its validity.

- Batters could benefit from ‘cognitive warm-up’ while waiting to bat in competition. While these are limited, such examples could include ball-tracking tasks and net-based warm-up (i.e., facing a bowler or having balls thrown to them). This will promote ball-tracking and allow batters to be adept to the forthcoming task.

8.5 Conclusions

This is the first study that has implemented direct measures of psychomotor function, visual attention, working memory, visual learning and memory and executive function during and after a prolonged batting simulation. The findings from this series of investigations provide several novel contributions to batting research. First, in amateur batters, prolonged batting periods inducing a physiological load of 64 $\%HR_{max}$ and above are sufficient to induce both muscular and cognitive impairments. The cognitive impairments associated with the simulation are most evident in psychomotor function, visual attention, working memory and executive functioning. One of the more significant findings to emerge from this study is that there are mitigating factors which increase the magnitude of batting-related cognitive impairment. The present data suggest that these are individual-specific and include, age, training status, playing experience and hydration levels. Importantly, this study shows that cognitive performance is also mediated by the type of physical activity required. Where previous studies have demonstrated beneficial effects of physical activity that is ‘purely physical’, this investigation shows that when physical activity requires continuous mental processing, the nature of impairment changes as does the intensity at which impairment occurs. Therefore, in sports where the athlete is required to perform a task that is both physically and cognitively demanding, application of conventional exercise literature may be misplaced. This study also extends knowledge on the physiological and muscular demands of prolonged batting periods, and provides recommendations to reduce performance decrements in these domains. It also highlights a number of issues with previous methodologies and, from the present methodology, provides future research direction(s). Future investigations need to enhance the ecological validity of cognitive testing in tasks like batting.

REFERENCE LIST

Abbiss, C. R., & Laursen, P. B. (2005). Models to explain fatigue during prolonged endurance cycling. *Sports Medicine*, 35(10), 865–898.

Afonso, J., Garganta, J., McRobert, A. P., Williams, A. M., & Mesquita, I. (2012). The perceptual cognitive processes underpinning skilled performance in volley-ball: Evidence from eye-movements and verbal reports of thinking involving an in situ representative task. *Journal of Sports Science and Medicine*, 11, 339–345.

Al-Ani, M., Munir, S., White, M., Townend, J., & Coote, J. H. (1996). Changes in R R variability before and after endurance training measured by power spectral analysis and by the effect of isometric muscle contraction. *European Journal of Applied Physiology*, 74, 397–403.

Alderman, B. L., & Olson, R. L. (2014). The relation of aerobic fitness to cognitive control and heart rate variability: A neurovisceral integration study. *Biological Psychology*, 99(1), 26–33.

Amann, M., Eldridge, M. W., Lovering, A. T., Stickland, M. K., Pegelow, D. F., & Dempsey, J. A. (2006). Arterial oxygenation influences central motor output and exercise performance via effects on peripheral locomotor muscle fatigue in humans. *The Journal of Physiology*, 575(3), 937–52.

An, H., Kulkarni, R., Nagarathna, R., & Nagendra, H. R. (2010). Measures of heart rate variability in women following a meditation technique. *International Journal of Yoga*, 3(1), 6–9.

Ando, S., Kokubu, M., Oda, S., Kimura, T., Hamada, T., & Moritani, T. (2005). Increase in reaction time for the peripheral visual field during exercise above the ventilatory threshold. *European Journal of Applied Physiology*, 94(4), 461–467.

Angevaren, M., Aufdemkampe, G., Verhaar, H. J. J., Aleman, A., & Vanhees, L. (2008). Physical activity and enhanced fitness to improve cognitive function in older people without known cognitive impairment. *Cochrane Database of Systematic Reviews*, 3, 2-73.

Ashnagar, Z., Shadmehr, A., & Jalaei, S. (2014). The effects of acute bout of cycling on auditory & visual reaction times. *Journal of Bodywork and Movement Therapies*, 1–5.

Audiffren, M. (2009). Acute exercise and psychological functions: a cognitive-energetic approach. In T. McMorris, P. Tomporowski, & M. Audiffren (Eds.), *Exercise and Cognitive Functioning*. Chichester, West Sussex: John Wiley and Sons.

Audiffren, M., Tomporowski, P. D., & Zagrodnik, J. (2008). Acute aerobic exercise and information processing: energizing motor processes during a choice reaction time task. *Acta Psychologica*, 129(3), 410–9.

Baddeley, A. D. (1992). Working Memory. *Science*, 255, 556–559.

Baddeley, A. D. (2010). Working memory. *Current Biology*, 20(4), 136–140.

Baddeley, A. D., & Hitch, G. J. (1974). Working Memory. In G. H. Bower (Ed.), Recent Advances in *Learning and Motivation* (8th ed.). New York, NY.: Academic Press.

Baden, D. A., McLean, T. L., Tucker, R., Noakes, T. D., & St Clair Gibson, A. (2005). Effect of anticipation during unknown or unexpected exercise duration on rating of perceived exertion, affect, and physiological function. *British Journal of Sports Medicine*, 39(10), 5.

Baechle, T., & Earle, R. (2008). *Essentials of Strength Training and Conditioning*. (R. Baechle, TR and Earle, Ed.) (3rd ed.). Champaign, IL: Human Kinetics.

Balaji, P., & Jesudass, E. S. (2011). Mental Toughness Differentials Among Cricket Players at Different Age Groups. *Recent Research in Science and Technology*, *3*(6), 54–56.

Barbieri, F. A., dos Santos, P. C. R., Vitório, R., van Dieën, J. H., & Gobbi, L. T. B. (2013). Effect of muscle fatigue and physical activity level in motor control of the gait of young adults. *Gait & Posture*, 38(4), 702–7.

Bartels, C., Wegrzyn, M., Wiedl, A., Ackermann, V., & Ehrenreich, H. (2010). Practice effects in healthy adults: A longitudinal study on frequent repetitive cognitive testing. *BMC Neuroscience*, 11, 118.

Beaudoin, D. (2012). The Effects of Fatiguing Exercise on Cognition and Physical Performance. *Unpublished Masters Thesis.* The University of British Columbia.

Benedict, R. H., & Zgaljardic, D. J. (1998). Practice effects during repeated administrations of memory tests with and without alternate forms. *Journal of Clinical and Experimental Neuropsychology*, 20(3), 339–352.

Berntson, G. G., Bigger, T., Eckberg, D. L., Grossman, P., Kaufman, P. G., Malik, M., ... Van Der Molen, M. W. (1997). Heart rate variability origins, methods, and interpretive caveats. *Psychophysiology*, 34, 623–648.

Billman, G. E. (2013). The LF/HF ratio does not accurately measure cardiac sympatho-vagal balance. *Frontiers in Physiology*, 4(26), 1–5.

Boecker, H., Hillman, C. H., Scheef, L., & Struder, H. K. (2012). *Functional Neuroimaging in Exercise and Sports Sciences*. New York, NY.: Springer.

Bogacz, R., Wagenmakers, E. J., Forstmann, B. U., & Nieuwenhuis, S. (2010). The neural basis of the speed-accuracy tradeoff. *Trends in Neurosciences*, 33(1), 10–16.

Borg, G. A. (1982). Psychophysical bases of perceived exertion. *Medicine & Science in Sports & Exercise*, 14(5), 377–381.

Bowyer, P. A., Humphreys, M. S., & Revelle, W. (1983). Arousal and recognition memory: The effects of impulsivity, caffeine and time on task. *Personality and Individual Differences*, 4(1), 41–49.

Braver, T. S. (2012). The variable nature of cognitive control: A dual-mechanisms framework. *Trends in Cognitive Sciences*, 16(2), 106–113.

Braver, T. S., Gray, J. R., & Burgess, G. C. (2007). Explaining the Many Varieties of Working Memory Variation: Dual Mechanisms of Cognitive Control. In A. Conway, C. Jarrold, & M. A. Kane (Eds.), *Variation in Working Memory* (pp. 76–106). Oxford University Press.

Brisswalter, J., Callardeau, M., & René, A. (2002). Effects of acute physical exercise on cognitive performance. *Sports Medicine*, 32(9), 555–566.

Brisswalter, J., Durand, M., Delignieres, D., & Legros, P. (1995). Optimal and non-optimal demand in a dual task of pedalling and simple reaction time: effects on energy expenditure and cognitive performance. *Journal of Human Movement Studies*, 29, 15–34.

Broadbent, D. E. (1957). A mechanical model for human attention and immediate memory. *Psychological Review*, 64(3), 205-215.

Bruyer, R., & Brysbaert, M. (2011). Combining speed and accuracy in cognitive psychology: Is the inverse efficiency score (IES) a better dependent variable than the mean reaction time (RT) and the percentage of errors (PE)? *Psychologica Belgica*, 51(1), 5–13.

Buchheit, M. (2014). Monitoring training status with HR measures: Do all roads lead to Rome? *Frontiers in Physiology*, 5, 1–19.

Budde, H., Brunelli, A., Machado, S., Velasques, B., Ribeiro, P., Arias-Carrión, O., & Voelcker-Rehage, C. (2012). Intermittent maximal exercise improves attentional performance only in physically active students. *Archives of Medical Research*, 43(2), 125–31.

Bullock, T., & Giesbrecht, B. (2014). Acute exercise and aerobic fitness influence selective attention during visual search. *Frontiers in Psychology*, 5, 1–11.

Burr, R. L. (2007). Interpretation of normalized spectral heart rate variability indices in sleep research: a critical review. *Sleep*, 30(7), 913–919.

Campher, J. (2008). The role of visual skills and its impact on skills performance of cricket players. *Unpublished Masters Thesis.* University of Pretoria.

Carrasco, A. J. (2008). Effects of exercise-induced dehydration on cognitive ability, muscular endurance and surfing performance. *Unpublished Masters Thesis.* Massey University.

Carter, J. B., Banister, E. W., & Blaber, A. P. (2003). Effect of Endurance Exercise on Autonomic Control of Heart Rate. *Sports Medicine*, 33(1), 33–46.

Casanova, F., Garganta, J., Silva, G., Alves, A., Oliveira, J., & Williams, A. M. (2013). Effects of prolonged intermittent exercise on perceptual-cognitive processes. *Medicine & Science in Sports & Exercise*, 45(8), 1610–7.

Casonatto, J., Tinucci, T., Dourado, C., & Polito, M. (2011). Cardiovascular and autonomic responses after exercise sessions with different intensities and durations. *Clinics*, 66(3), 453–458.

Chan, R. C. K., Shum, D., Toulopoulou, T., & Chen, E. Y. H. (2008). Assessment of executive functions: Review of instruments and identification of critical issues. *Archives of Clinical Neuropsychology*, 23, 201–216.

Chang, Y. K., Etnier, J. L., & Barella, L. A. (2009). Exploring the Relationship Between Exercise- Induced Arousal and Cognition Using Fractionated Response Time. *Research Quarterly for Exercise and Sport*, 80(1), 78–86.

Chang, Y. K., Labban, J. D., Gapin, J. I., & Etnier, J. L. (2012). The effects of acute exercise on cognitive performance: A meta-analysis. *Brain Research*, 1453(April 2016), 87–101.

Chang, Y. K., Tsai, C. L., Hung, T. M., So, E. C., Chen, F. T., & Etnier, J. L. (2011). Effects of acute exercise on executive function: A study with a Tower of London Task. *Journal of Sport & Exercise Psychology*, 33, 847–865.

Chmura, J., Krysztofiak, H., Ziemba, A. W., Nazar, K., & Kaciuba-Uscilko, H. (1998). Psychomotor performance during prolonged exercise above and below the blood lactate threshold. *European Journal of Applied Physiology*, 77, 77–80.

Christie, C. J. (2008). The Physical Demands of Batting and Fast Bowling in Cricket. In K. Zaslav (Ed.), *An International Perspective on Topics in Sports Medicine and Sports Injury* (pp. 321–331). Rijeka, Croatia: InTech.

Christie, C. J., & Pote, L. (2014). Physiological and Perceptual Demands of High Intensity Sprinting Between the Wickets in Cricket. *International Journal of Sports Science & Coaching*, 9(6), 1375–1382.

Christie, C. J., Sheppard, B. J., Goble, D., Pote, L., & Noakes, T. D. (2016). Effects of two different cricket-specific interval running tests on sprint speed and development of lower limb muscle fatigue. *Unpublished Data*.

Christie, C. J., Todd, A. I., & King, G. A. (2008). Selected physiological responses during batting in a simulated cricket work bout: a pilot study. *Journal of Science and Medicine in Sport*, 11(6), 581–4.

Cinaz, B., Arnrich, B., La Marca, R., & Tröster, G. (2013). Monitoring of mental workload levels during an everyday life office-work scenario. *Personal and Ubiquitous Computing*, 17(2), 229–239.

Cognition. (2016). In *Encyclopaedia Britannica*. Retrieved from http://global.britannica.com/topic/cognition-thought-process.

Coles, K., & Tomporowski, P. D. (2008). Effects of acute exercise on executive processing, short-term and long-term memory. *Journal of Sports Sciences*, 26(3), 333–344.

Collardeau, M., Brisswalter, J., & Audiffren, M. (2001). Effects of a Prolonged Run on Simple Reaction Time of Well Trained Runners. *Perceptual and Motor Skills*, 93(3), 679–689.

Collardeau, M., Brisswalter, J., Vercruyssen, F., Audiffren, M., & Goubault, C. (2001). Single and choice reaction time during prolonged exercise in trained subjects: Influence of carbohydrate availability. *European Journal of Applied Physiology*, 86(2), 150–156.

Collie, A., Darby, D., & Maruff, P. (2001). Computerised cognitive assessment of athletes with sports related head injury. British Journal of Sports Medicine, 35, 297–302.

Cometti, G., Maffiuletti, N. a, Pousson, M., Chatard, J. C., & Maffulli, N. (2001). Isokinetic strength and anaerobic power of elite, subelite and amateur French soccer players. *International Journal of Sports Medicine*, 22(1), 45–51.

Corrales, M. M., de la Cruz Torres, B., Esquivel, A. G., Salazar, A. M. G., & Orellana, J. N. (2012). Normal values of heart rate variability at rest in a young, healthy and active Mexican population. *Health*, 4(7), 377–385.

Cote, J., & Salmela, J. (1992). Effects of Progressive Exercise on Attentional Focus. *Perceptual and Motor Skills*, 75, 351–354.

Crewe, H., Tucker, R., & Noakes, T. D. (2008). The rate of increase in rating of perceived exertion predicts the duration of exercise to fatigue at a fixed power output in different environmental conditions. *European Journal of Applied Physiology*, 103(5), 569–577.

Croft, J. L., Button, C., & Dicks, M. (2010). Visual strategies of sub-elite cricket batsmen in response to different ball velocities. *Human Movement Science*, 29(5), 751–63.

Cumming, G. (2014). The new statistics: Why and how. *Psychological Science*, 25(1), 7–29.

D'Anci, K. E., Mahoney, C. R., Vibhakar, A., Kanter, J. H., & Taylor, H. A. (2009). Voluntary dehydration and cognitive performance in trained college athletes. *Perceptual and Motor Skills*, 109(1), 251–269.

Daanen, H. A. M., Lamberts, R. P., Kallen, V. L., Jin, A., & Van Meeteren, N. L. U. (2012). A systematic review on heart-rate recovery to monitor changes in training status in athletes. *International Journal of Sports Physiology and Performance*, 7(3), 251–260.

Darby, D. G., Moriarity, J. G., Pietrzak, R. H., Kutcher, J. S., McAward, K., & McCrory, P. (2014). Prediction of winning amateur boxers using pre-tournament reaction times. *Journal of Sports Medicine and Physical Fitness*, 54(3), 340–346.

Davranche, K., & Audiffren, M. (2004). Facilitating effects of exercise on information processing. *Journal of Sports Sciences*, 22(5), 419–28.

Davranche, K., Burle, B., Audiffren, M., & Hasbroucq, T. (2005). Information processing during physical exercise: A chronometric and electromyographic study. *Experimental Brain Research*, 165(4), 532–540.

Davranche, K., Burle, B., Audiffren, M., & Hasbroucq, T. (2006). Physical exercise facilitates motor processes in simple reaction time performance: An electromyographic analysis. *Neuroscience Letters*, 396(1), 54–56.

de Koning, J. J., Foster, C., Bakkum, A., Kloppenburg, S., Thiel, C., Joseph, T., ... Porcari, J. P. (2011). Regulation of pacing strategy during athletic competition. *PloS One*, 6(1), e15863.

De Morree, H. M., & Marcora, S. M. (2013). Effects of isolated locomotor muscle fatigue on pacing and time trial performance. *European Journal of Applied Physiology*, 113(9), 2371–2380.

Del Giorno, J. M., Hall, E. E., O'Leary, K. C., Bixby, W. R., & Miller, P. C. (2010). Cognitive function during acute exercise: a test of the transient hypofrontality theory. *Journal of Sport & Exercise Psychology*, 32(3), 312–323.

Diamond, A. (2015). Effects of Physical Exercise on Executive Functions: Going beyond Simply Moving to Moving with Thought. *Annals of Sports Medicine and Research*, 2(1), 1011.

DiDomenico, A., & Nussbaum, M. A. (2011). Effects of different physical workload parameters on mental workload and performance. *International Journal of Industrial Ergonomics*, 41(3), 255–260.

Dietrich, A. (2009). Transient Hypofrontality Theory. In T. McMorris, P. D. Tomporowski, & M. Audiffren (Eds.), *Exercise and Cognitive Functioning*. Chichester, West Sussex: John Wiley and Sons.

Dietrich, A., & Audiffren, M. (2011). The reticular-activating hypofrontality (RAH) model of acute exercise. *Neuroscience & Biobehavioral Reviews*, 35(6), 1305–1325.

Draper, S., McMorris, T., & Parker, J. K. (2010). Effect of acute exercise of differing intensities on simple and choice reaction and movement times. *Psychology of Sport and Exercise*, 11(6), 536–541.

Duffield, R., & Drinkwater, E. J. (2008). Time-motion analysis of Test and One-Day international cricket centuries. *Journal of Sports Sciences*, 26(5), 457–64.

Elliot, A. J., Payen, V., Brisswalter, J., Cury, F., & Thayer, J. F. (2011). A subtle threat cue, heart rate variability, and cognitive performance. *Psychophysiology*, 48(10), 1340–1345.

Elliott, A. (2014). Impact of batting skill on pacing during repeated sprints between the wickets. *Unpublished Masters Thesis*. Rhodes University.

Enoka, R. M. (1995). Mechanisms of muscle fatigue: Central factors and task dependency. *Journal of Electromyography and Kinesiology*, 5(3), 141–9.

Enoka, R. M. (1996). Eccentric contractions require unique activation strategies by the nervous system. *Journal of Applied Physiology*, 81, 2339–2346.

ESPNCricinfo. (2016). *Statistics/Statsguru*. Retrieved 16 September 2016, from http://stats.espncricinfo.com/ci/engine/stats/index.html

Etnier, J. L., & Chang, Y. K. (2009). The effect of physical activity on executive function: a brief commentary on definitions, measurement issues, and the current state of the literature. *Journal of Sport & Exercise Psychology*, 31(4), 469–483.

Falleti, M. G., Maruff, P., Collie, A., & Darby, D. G. (2006). Practice effects associated with the repeated assessment of cognitive function using the CogState battery at 10-minute, one week and one month test-retest intervals. *Journal of Clinical and Experimental Neuropsychology*, 28(7), 1095–112.

Fletcher, J. G. (1955). Calories in Cricket. *The Lancet*, 4, 1165–1166.

Foskett, A., Ali, A., & Gant, N. (2009). Caffeine enhances cognitive function and skill performance during simulated soccer activity. *International Journal of Sport Nutrition and Exercise Metabolism*, 19(4), 410–23.

Freeman, J. V, Dewey, F. E., Hadley, D. M., Myers, J. J., & Froelicher, V. F. (2006). Autonomic Nervous System Interaction With the Cardiovascular System During Exercise. *Progress in Cardiovascular Diseases*, 48(5), 342–362.

Gandevia, S. C. (2001). Spinal and supraspinal factors in human muscle fatigue. *Physiological Reviews*, 81(4), 1725–89.

Ganio, M. S., Armstrong, L. E., Casa, D. J., McDermott, B. P., Lee, E. C., Yamamoto, L. M., ... Lieberman, H. R. (2011). Mild dehydration impairs cognitive performance and mood of men. *British Journal of Nutrition*, 106(10), 1535–1543.

Gastin, P. B. (2001). Energy system interaction and relative contribution during maximal exercise. *Sports Medicine*, 31(10), 725–741.

Girard, O., Lattier, G., Maffiuletti, N. A., Micallef, J., & Millet, G. P. (2008). Neuromuscular fatigue during a prolonged intermittent exercise: Application to tennis. *Journal of Electromyography and Kinesiology*, 18(6), 1038–46.

Glazier, P., Davids, K., & Bartlett, R. M. (2002). Grip force dynamics in cricket batting. In *Interceptive Actions in Sport: Information and Movement* (pp. 312–326). NY: Routledge.

Goble, D., & Christie, C. J. (2016). Cognitive, physical and physiological responses of school boy cricketers to a 30-over batting simulation 30-over batting simulation. *Journal of Sport Sciences*, 1–7.

Goldberger, J. J., Challapalli, S., Tung, R., Parker, M. A., & Kadish, A. H. (2001). Relationship of heart rate variability to parasympathetic effect. *Circulation*, 103(15), 1977–1983.

Goldstein, D. S., Bentho, O., Park, M., & Sharabi, Y. (2011). Low-frequency power of heart rate variability is not a measure of cardiac sympathetic tone but may be a measure of modulation of cardiac autonomic outflows by baroreflexes. *Experimental Physiology*, 96(12), 1255–61.

Gore, C. J., Bourdon, P. C., Woolford, S. M., & Pederson, D. G. (1993). Involuntary Dehydration During Cricket. *International Journal of Sports Medicine*, 14(7), 387–395.

Gore, C. J., Bourdon, P. C., Woolford, S. M., & Pederson, D. G. (1994). Fluid balance during cricket. National Sports Research Centre.

Greig, M., Marchant, D., Lovell, R., Clough, P., & McNaughton, L. (2007). A continuous mental task decreases the physiological response to soccer-specific intermittent exercise. *British Journal of Sports Medicine*, 41(12), 908–13.

Gurd, J. M., Kischka, U., & Marshall, J. C. (2010). *Handbook of Clinical Neuropsychology*. Oxford University Press.

Halliwill, J. R., Buck, T. M., Lacewell, A. N., & Romero, S. A. (2013). Postexercise hypotension and sustained postexercise vasodilatation: what happens after we exercise? *Experimental Physiology*, 1, 7–18.

Hansen, A. L., Johnsen, B. H., & Thayer, J. F. (2003). Vagal influence on working memory and attention. *International Journal of Psychophysiology*, 48(3), 263–274.

Hatfield, B. D., Haufler, A. J., Hung, T., & Spalding, T. W. (2004). Electroencephalographic studies of skilled psychomotor performance. *Journal of Clinical Neurophysiology : Official Publication of the American Electroencephalographic Society*, *21*(3), 144–156.

Hill, A. V., Long, C. N. H. & Lupton, H. (1924a). Muscular exercise, lactic acid and the supply and utilisation of oxygen. Parts I–III. *Proceedings of the Royal Society of London*. 97, 438–475.

Hill, A. V., Long, C. N. H. and Lupton, H. (1924b). Muscular exercise, lactic acid and the supply and utilisation of oxygen. Parts VII–VII. *Proceedings of the Royal Society of London*. 97, 155–176.

Hillman, C. H., Apparies, R. J., Janelle, C. M., & Hatfield, B. D. (2000). An electrocortical comparison of executed and rejected shots in skilled marksmen. *Biological Psychology*, *52*(1), 71–83.

Hillman, C. H., Snook, E. M., & Jerome, G. J. (2003). Acute cardiovascular exercise and executive control function. *International Journal of Psychophysiology*, 48(3), 307–314.

Hillyer, M., Menon, K., & Singh, R. (2015). The Effects of Dehydration on Skill-Based Performance. *International Journal of Sports Science*, 5(3), 99–107.

Hjortskov, N., Rissen, D., Blangsted, A. K., Fallentin, N., Lundberg, U., & Sogaard, K. (2004). The effect of mental stress on heart rate variability and blood pressure during computer work. *European Journal of Applied Physiology*, 92(1–2), 84–89.

Hogervorst, E. W. R., Jeukendrup, A. E., & Jolles, J. (1996). Cognitive Performance After Strenuous Physical Exercise. *Perceptual and Motor Skills*, 83(2), 479–488.

Holt, N. L. Coping in Professional Sport: A Case Study of an Experienced Cricket Player (2003).

Holtzer, R., Shuman, M., Mahoney, J. R., Lipton, R., & Verghese, J. (2012). Cognitive Fatigue Defined in the Context of Attention Networks. *Neuropsychology, Development, and Cognition*, 18(1), 108–128.

Houghton, L., & Dawson, B. (2012). Short report: Recovery of jump performance after a simulated cricket batting innings. *Journal of Sports Sciences*, 30(10), 1069–72.

Houghton, L., Dawson, B., & Rubenson, J. (2011a). Performance in a simulated cricket batting innings (BATEX): reliability and discrimination between playing standards. *Journal of Sport Sciences*, 29(10), 1097–103.

Houghton, L., Dawson, B., Rubenson, J., & Tobin, M. (2011b). Movement patterns and physical strain during a novel, simulated cricket batting innings (BATEX). *Journal of Sports Sciences*, 29(8), 801–9.

Houghton, L., Dawson, B., & Rubenson, J. (2013). Effects of Plyometric Training on Achilles Tendon Properties and Shuttle Running During a Simulated Cricket Batting Innings. *Journal of Strength and Conditioning Research*, *27*(4), 1036–1046.

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

Javorka, M., Zila, I., Balhárek, T., & Javorka, K. (2002). Heart rate recovery after exercise: relations to heart rate variability and complexity. *Brazilian Journal of Medical and Biological Research*, 35(35), 991–1000.

Jeukendrup, A. E. (2007). Carbohydrate Supplementation During Exercise: Does It Help? How Much Is Too Much? *Sport Science Exchange*, 20(3).

Job, R. F. S., & Dalziel, J. (2001). Defining fatigue as a condition of the organism and distinguishing it from habituation, adaptation, and boredom. In P. A. Hancock & P. A. Desmond (Eds.), *Stress, Workload and Fatigue*. Mahwah, N J: Lawrence Erlbaum Associates.

Johnstone, J. A., & Ford, P. A. (2010). Physiologic Profile of Professional Cricketers. *Journal of Strength and Conditioning Research*, 24(11), 2900–2907.

Joste, J. (2012). *The relationship between mental skills and level of cricket participation*. Unpublished Master's Thesis, University of Pretoria.

Jorna, P. G. A. M. (1992). Spectral analysis of heart rate and psychological state: A review of its validity as a workload index. *Biological Psychology*, 34(2–3), 237–257.

Kahneman, D. (1973). *Attention and effort*. Englewood Cliffs, New Jersey: Prentice-Hall Inc.

Kamath, M. V, Fallen, E. L., & McKelvie, R. (1991). Effects of steady state exercise on the power spectrum of heart rate variability. *Medicine & Science in Sports & Exercise*, 23(4), 428–434.

Kamijo, K., Hayashi, Y., Sakai, T., Yahiro, T., Tanaka, K., & Nishihira, Y. (2009). Acute effects of aerobic exercise on cognitive function in older adults. *Journal of Gerontology*, 64(3), 356–63.

Kamijo, K., Nishihira, Y., Hatta, A., Kaneda, T., Wasaka, T., Kida, T., & Kuroiwa, K. (2004). Differential influences of exercise intensity on information processing in the central nervous system. *European Journal of Applied Physiology*, 92(3), 305–11.

Kamijo, K., Nishihira, Y., Higashiura, T., Hatta, A., Kaneda, T., Kim, S., & Kim, B. (2006). Influences of exercise intensity on cognitive processing and arousal level in the central nervous system. *Advances in Exercise and Sports Physiology*, 12(1), 1–7.

Kashihara, K., & Nakahara, Y. (2005). Short-term effect of physical exercise at lactate threshold on choice reaction time. *Perceptual and Motor Skills*, 100(1998), 275–291.

Katsumata, H., & Russell, D. M. (2012). Prospective versus predictive control in timing of hitting a falling ball. *Experimental Brain Research*, 216(4), 499–514.

Kay, D., St Clair Gibson, A., Mitchell, M. J., Lambert, M. I., & Noakes, T. D. (2000). Different neuromuscular recruitment patterns during eccentric, concentric and isometric contractions. *Journal of Electromyography and Kinesiology*, 10(6), 425–31.

King, G. A., Christie, C. J., & Todd, A. I. (2002). Effect of protective gear on skin temperature responses and sweat loss during batting. *Sports Medicine*, 30–35.

Knapp, K., & Morton, J. (2013). Brain development and executive functioning. In *Encyclopedia on Early Childhood Development* (pp. 1–7).

Kruger, P. E., Campher, J., & Smit, C. E. (2009). The role of visual skills and its impact on skill performance of cricket players. *African Journal for Physical, Health Education, Recreation and Dance*, 15(4), 605–623.

Lambert, E. V, St Clair Gibson, A., & Noakes, T. D. (2005). Complex systems model of fatigue: integrative homoeostatic control of peripheral physiological systems during exercise in humans. *British Journal of Sports Medicine*, 39(1), 52–62.

Lambourne, K., & Tomporowski, P. D. (2010). The effect of exercise-induced arousal on cognitive task performance: A meta-regression analysis. *Brain Research*, 1341, 12–24.

Land, M. F., & McLeod, P. (2000). From eye movements to actions: how batsmen hit the ball. *Nature Neuroscience*, 3(12), 1340–5.

Lemmink, K. A. P. M., & Visscher, C. (2005). Effect of intermittent exercise on multiple-choice reaction times of soccer players. *Perceptual and Motor Skills*, 100, 85–95.

Lenneman, L. M., Sidrow, K. M., Johnson, E. M., Harrison, C. R., Vojta, C. N., & Walker, T. B. (2013). The Influence of Agility Training on Physiological and Cognitive Performance. *Journal of Strength and Conditioning Research*, 27(12), 3300–3309.

Lockie, R. G., Jeffriess, M. D., & Callaghan, S. J. (2012). Running velocity during the run-a-three in experienced cricketers. *Serbian Journal of Sports Sciences*, 6(3), 103–110.

Loock, N., Du Toit, D. E., Ventner, D. J. L., & Stretch, R. a. (2006). Effect of different types of cricket batting pads on the running and turning speed in cricket batting. *Sports Biomechanics / International Society of Biomechanics in Sports*, *5*(1), 15–22.

Loram, L. C., McKinon, W., Wormgoor, S., Rogers, G. G., Nowak, I., & Harden, L. M. (2005). Determinants of ball release speed in schoolboy fast-medium bowlers in cricket. *Journal of Sports Medicine and Physical Fitness*, 45, 483–490.

Lorist, M. M., & Snel, J. (1997). Caffeine effects on perceptual and motor processes. *Electroencephalography and Clinical Neurophysiology*, 102(5), 401–413.

Lounana, J., Campion, F., Noakes, T. D., & Medelli, J. (2007). Relationship between %HRmax, %HR reserve, %VO2max, and %VO2 reserve in elite cyclists. *Medicine & Science in Sports & Exercise*, 39(2), 350–357.

Lovell, R., Midgley, A., Barrett, S., Carter, D., & Small, K. (2013). Effects of different half-time strategies on second half soccer-specific speed, power and dynamic strength. *Scandinavian Journal of Medicine & Science in Sports*, 23(1), 105–13.

Lowe, C. J., Hall, P. A., Vincent, C. M., & Luu, K. (2014). The effects of acute aerobic activity on cognition and cross-domain transfer to eating behavior. *Frontiers in Human Neuroscience*, 8, 1–7.

Luft, C. D., Takase, E., & Darby, D. (2009). Heart rate variability and cognitive function: effects of physical effort. *Biological Psychology*, 82(2), 164–168.

Luque-Casado, A., Perales, J. C., Cárdenas, D., & Sanabria, D. (2015). Heart rate variability and cognitive processing: The autonomic response to task demands. *Biological Psychology*, 113, 83–90.

Luque-Casado, A., Zabala, M., Morales, E., Mateo-March, M., & Sanabria, D. (2013). Cognitive Performance and Heart Rate Variability: The Influence of Fitness Level. *PloS One*, 8(2).

MacIntosh, B. r, & Rassier, D. e. (2002). What is fatigue? Canadian *Journal of Applied Physiology*, 27(1), 42–55.

Malik, M., Bigger, J. T., Camm, A. J., & Kleiger, R. E. (1996). Heart rate variability. Standards of measurement, physiological interpretation, and clinical use. Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology. *European Heart Journal*, 17, 354–381.

Malliani, A., Lombardi, F., & Pagani, M. (1994). Power spectrum analysis of heart rate variability: A tool to explore neural regulatory mechanisms. *British Heart Journal*, 71, 1–2.

Mann, D. L., Abernethy, B., & Farrow, D. (2010). Action specificity increases anticipatory performance and the expert advantage in natural interceptive tasks. *Acta Psychologica*, 135(1), 17–23.

Mann, D. T. Y., Williams, A. M., Ward, P., & Janelle, C. M. (2007). Perceptual-cognitive expertise in sport: a meta-analysis. *Journal of Sport & Exercise Psychology*, 29(4), 457–78.

Mansingh, A., Harper, L., Headley, S., King-Mowatt, J., & Mansingh, G. (2006). Injuries in West Indies cricket 2003-2004. *British Journal of Sports Medicine*, 40(2), 119-23-23.

Marcora, S. M. (2008). Do we really need a central governor to explain brain regulation of exercise performance? *European Journal of Applied Physiology*, 104(5), 929–931.

Marcora, S. M. (2010). Last Word on Point: Counterpoint: Afferent feedback from fatigued locomotor muscles is not an important determinant of endurance exercise performance. *Journal of Applied Physiology*, 108, 458–468.

Marcora, S. M., Bosio, A., & de Morree, H. M. (2008). Locomotor muscle fatigue increases cardiorespiratory responses and reduces performance during intense cycling exercise independently from metabolic stress. *American Journal of Physiology. Regulatory, Integrative and Comparative Physiology*, 294(3), R874–R883.

Marcora, S. M., & Staiano, W. (2010). The limit to exercise tolerance in humans: mind over muscle? *European Journal of Applied Physiology*, 109(4), 763–70.

Marcora, S. M., Staiano, W., & Manning, V. (2009). Mental fatigue impairs physical performance in humans. *Journal of Applied Physiology*, *106*, 857–864.

Markovic, G., Dizdar, D., Jukic, I., & Cardinale, M. (2004). Reliability and factorial validity of squat and countermovement jump tests. *Journal of Strength and Conditioning Research*, 18(3), 551–555.

Marois, R., & Ivanoff, J. (2005). Capacity limits of information processing in the brain. *Trends in Cognitive Sciences*, 9(6), 296–305.

Maruff, P., Falleti, M. G., Collie, A., Darby, D., & McStephen, M. (2005). Fatigue-related impairment in the speed, accuracy and variability of psychomotor performance: comparison with blood alcohol levels. *Journal of Sleep Research*, 14, 21–27.

Maruff, P., Thomas, E., Cysique, L., Brew, B., Collie, A., Snyder, P., & Pietrzak, R. H. (2009). Validity of the CogState brief battery: relationship to standardized tests and sensitivity to cognitive impairment in mild traumatic brain injury, schizophrenia, and AIDS dementia complex. *Archives of Clinical Neuropsychology*, 24(2), 165–78.

Mateo, M., Blasco-Lafarga, C., Martinez-Navarro, I., Guzman, J. F., & Zabala, M. (2012). Heart rate variability and pre-competitive anxiety in BMX discipline. *European Journal of Applied Physiology*, 112(1), 113–123.

Matlin, M. W. (2008). *Cognition* (8th ed.). John Wiley and Sons.

Matthews, G., & Desmond, P. A. (2007). Task-induced fatigue states and simulated driving performance. *The Quarterly Journal of Experimental Psychology*, 55(2), 659–686.

McArdle, D. W., Katch, F. I., & Katch, V. L. (2006). *Essentials of Exercise Physiology*. (3rd ed.). Baltimore, MD: Lippincott Williams & Wilkins.

McCabe, D. P., McDaniel, M. a, & Hambrick, D. Z. (2010). The Relationship Between Working Memory Capacity and Executive Functioning: Evidence for a Common Executive Attention Construct. *Neuropsychology*, 24(2), 222–243.

McCaffrey, R. J., Ortega, A., & Haase, R. F. (1993). Effects of repeated neuropsychological assessments. *Archives of Clinical Neuropsychology*, 8(6), 519–524.

McCallum, C. W. (2016). Attention. In *Encyclopedia Britannica*. Retrieved from http://global.britannica.com/topic/attention.

McDuff, D., Gontarek, S., & Picard, R. (2014). Remote Measurement of Cognitive Stress via Heart Rate Variability. In *Proceedings of 36th Annual International Conference of the IEEE Engineering in Medicine and Biology Society* (EMBC) (pp. 2957–2960).

McGlynn, G. H., Laughlin, N. T., & Bender, V. L. (1977). Effects of Strenous to Exhaustive exercise on a Discrimination Task. *Perceptual and Motor Skills*, 44, 1139–1147.

McGuigan, M. R., Doyle, T. L. A., Newton, M., Edwards, D. J., Nimphius, S., & Newton, R. U. (2006). Eccentric utilization ratio: effect of sport and phase of training. *Journal of Strength and Conditioning Research*, 20(4), 992–995.

Mckellar, D. M., Nurick, G. N., & Stretch, R. A. (1998). The measurement of the position of a ball striking a cricket bat. In S. J. Hooke (Ed.), *The Engineering of Sport: Design and Development* (pp. 275–282). Cambridge: UK: University Press.

McMorris, T. (2009). Exercise and cognitive function: A neuroendocrinological explanation. In T. McMorris, P. D. Tomporowski, & M. Audiffren (Eds.), *Exercise and Cognitive Functioning* (pp. 41–68). Chichester, West Sussex: John Wiley and Sons.

McMorris, T., Delves, S., Sproule, J., Lauder, M., & Hale, B. (2005). Effect of incremental exercise on initiation and movement times in a choice response, whole body psychomotor task. *British Journal of Sports Medicine*, 39(8), 537–41.

McMorris, T., & Graydon, J. (1997). The effect of exercise on cognitive performance in soccer-specific tests. *Journal of Sports Sciences*, 15(5), 459–468.

McMorris, T., Hill, C., Sproule, J., Potter, J., Swain, J., Hobson, G., & Holder, T. (2005). Supra-maximal effort and reaction and movement times in a non-compatible response time task. *Journal of Sports Medicine and Physical Fitness*, 45(1), 127–133.

McMorris, T., Sproule, J., Turner, A., & Hale, B. (2011). Acute, intermediate intensity exercise, and speed and accuracy in working memory tasks: A meta-analytical comparison of effects. *Physiology and Behavior*, 102(3–4), 421–428.

McMorris, T., Tallon, M., Williams, C., Sproule, J., Draper, S., Swain, J., … Clayton, N. (2003). Incremental exercise, plasma concentrations of catecholamines, reaction time, and motor time during performance of a noncompatible choice response time task. *Perceptual and Motor Skills*, 97(2), 590–604.

McMorris, T., Tomporowski, P. D., & Audiffren, M. (2009). *Exercise and Cognitive Function* (1st ed.). Chichester, West Sussex: John Wiley and Sons.

McRobert, A. P., Ward, P., Eccles, D. W., & Williams, A. M. (2011). The effect of manipulating context-specific information on perceptual-cognitive processes during a simulated anticipation task. *British Journal of Psychology*, 102(3), 519–34.

Micklewright, D., Papadopoulou, E., Swart, J., & Noakes, T. (2010). Previous experience influences pacing during 20 km time trial cycling. *British Journal of Sports Medicine*, 44(13), 952–960.

Montano, N., Ruscone, T. G., Porta, A., Lombardi, F., Pagani, M., & Malliani, A. (1994). Power spectrum analysis of heart rate variability to assess the changes in sympathovagal balance during graded orthostatic tilt. *Circulation*, 90(4), 1826–1831.

Moray, N. (1967). Where is attention limited? A survey and a model. *Acta Psychologica*, 27, 84–92.

Morris, J. G., Nevill, M. E., Lakomy, H. K. A., Nicholas, C., & Williams, C. (2010). Effect of a hot environment on performance of prolonged, intermittent, high-intensity shuttle running. *Journal of Sports Sciences*, 16(7), 667–686.

Mukherjee, S., Yadav, R., Yung, I., Zajdel, D. P., & Oken, B. S. (2011). Sensitivity to mental effort and test-retest reliability of heart rate variability measures in healthy seniors. *Clinical Neurophysiology*, 122(10), 2059–2066.

Müller, S., & Abernethy, B. (2006). Batting with occluded vision: an in situ examination of the information pick-up and interceptive skills of high- and low-skilled cricket batsmen. *Journal of Science and Medicine in Sport*, 9(6), 446–58.

Müller, S., Abernethy, B., & Farrow, D. (2006). How do world-class cricket batsmen anticipate a bowler's intention? *The Quarterly Journal of Experimental Psychology*, 59(12), 2162–86.

Müller, S., Abernethy, B., Reece, J., Rose, M., Eid, M., McBean, R., ... Abreu, C. (2009). An in-situ examination of the timing of information pick-up for interception by cricket batsmen of different skill levels. *Psychology of Sport and Exercise*, 10(6), 644–652.

Müller, S., Brenton, J., Dempsey, R., Harbaugh, A. G., & Reid, C. (2015). Individual differences in highly skilled visual perceptual-motor striking skill. *Attention, Perception & Psychophysics*, 77(2).

Neave, N., Emmett, J., Moss, M., Ayton, R., Scholey, A., & Wesnes, K. (2004). The Effects of Protective Helmet Use on Physiology and Cognition in Young Cricketers. *Applied Cognitive Psychology*, 18, 1181–1193.

Netz, Y., Wu, M., Becker, B. J., & Tenenbaum, G. (2005). Physical activity and psychological well-being in advanced age: a meta-analysis of intervention studies. *Psychology and Aging*, 20(2), 272–84.

Nickel, P., & Nachreiner, F. (2003). Sensitivity and diagnosticity of the 0.1-Hz component of heart rate variability as an indicator of mental workload. *Human Factors*, 45(4), 575–590.

Nicol, C., Komi, P. V, & Marconnet, P. (1991). Fatigue effects of marathon running on neuromuscular fatigue. Changes in muscle force and stiffness characteristics. *Scandinavian Journal of Medicine & Science in Sports*, 1, 10–17.

Noakes, T. D. (2000). Physiological models to understand exercise fatigue and the adaptations that predict or enhance athletic performance. *Scandinavian Journal of Medicine & Science in Sports*, 10, 123–145.

Noakes, T. D., & Durandt, J. J. (2000). Physiological requirements of cricket. *Journal of Sport Sciences*, 18(12), 919–929.

Noakes, T. D., Peltonen, J. E., & Rusko, H. K. (2001). Evidence that a central governor regulates exercise performance during acute hypoxia and hyperoxia. *The Journal of Experimental Biology*, 204(Pt 18), 3225–34.

Noakes, T. D., St Clair Gibson, A., & Lambert, E. V. (2005). From catastrophe to complexity: a novel model of integrative central neural regulation of effort and fatigue during exercise in humans: summary and conclusions. *British Journal of Sports Medicine*, 39(2), 120–4.

Noble, C. E. (2016). Psychomotor Learning. In *Encyclopaedia Britannica*. Retrieved from http://global.britannica.com/topic/psychomotor-learning.

Norman, D. A., & Bobrow, D. G. (1975). On data-limited and resource limited processes. *Cognitive Psychology*, 7, 44–64.

Nunes, T., & Coetzee, B. (2007). The contribution of isokinetic strength parameters to the performance of cricket batsmen. *Biokinetics and Exercise Science*, 15, 233–244.

Orchard, J. W., James, T., Alcott, E., Carter, S., & Farhart, P. (2002). Injuries in Australian cricket at first class level 1995/1996 to 2000/2001. *British Journal of Sports Medicine*, 36(4), 270–4; discussion 275.

Orchard, J. W., James, T., Kountouris, A., & Portus, M. R. (2010). Changes to injury profile (and recommended cricket injury definitions) based on the increased frequency of Twenty20 cricket matches. *Open Access Journal of Sports Medicine*, 1, 63–76.

Orchard, J. W., James, T., & Portus, M. R. (2006). Injuries to elite male cricketers in Australia over a 10-year period. *Journal of Science and Medicine in Sport*, 9(6), 459–67.

Pagani, M., Lombardi, F., Guzzetti, S., Rimoldi, O., Furlan, R., Pizzinelli, P., ... Piccaluga, E. (1986). Power spectral analysis of heart rate and arterial pressure variabilities as a marker of sympatho-vagal interaction in man and conscious dog. *Circulation Research*, 59(2), 178–193.

Pageaux, B. (2014). The Psychobiological Model of Endurance Performance: An Effort-Based Decision-Making Theory to Explain Self-Paced Endurance Performance. *Sports Medicine*, 1319–1320.

Pageaux, B., Lepers, R., Dietz, K. C., & Marcora, S. M. (2014). Response inhibition impairs subsequent self-paced endurance performance. *European Journal of Applied Physiology*, 114(5), 1095–1105.

Pageaux, B., Marcora, S. M., & Lepers, R. (2013). Prolonged mental exertion does not alter neuromuscular function of the knee extensors. *Medicine & Science in Sports & Exercise*, 45(12), 2254–2264.

Pageaux, B., Marcora, S. M., Rozand, V., & Lepers, R. (2015). Mental fatigue induced by prolonged self-regulation does not exacerbate central fatigue during subsequent whole-body endurance exercise. *Frontiers in Human Neuroscience*, 9(February), 67.

Papaioannou, A. G., & Hackfort, D. (2014). *Routledge Companion to Sport and Exercise Psychology: Global Perspectives and Fundamental Concepts*. (A. G. Papaioannou & D. Hackfort, Eds.). New York, NY.: Routledge.

Peçanha, T., de Paula-Ribeiro, M., Nasario-Junior, O., & de Lima, J. R. P. (2013). Post-exercise heart rate variability recovery: A time-frequency analysis. *Acta Cardiologica*, 68(6), 607–613.

Penn, M. J., & Spratford, W. (2012). Are current coaching recommendations for cricket batting technique supported by biomechanical research? *Sports Biomechanics*, 11(3), 311–23.

Pesce, C., Capranica, L., Tessitore, A., & Figura, F. (2003). Focusing of visual attention under submaximal physical load. *International Journal of Sport and Exercise Psychology*, 1(3), 275–292.

Petersen, C. J., Pyne, D., Dawson, B., Portus, M. R., & Kellett, A. (2010). Movement patterns in cricket vary by both position and game format. *Journal of Sports Sciences*, 28(1), 45–52.

Petersen, C. J., Pyne, D., Portus, M. R., & Dawson, B. (2009). Quantifying positional movement patterns in Twenty20 cricket. *International Journal of Performance Analysis of Sport*, 9, 165–170.

Petersen, C. J., Pyne, D., Portus, M. R., & Dawson, B. (2011). Comparison of Player Movement Patterns Between 1-Day and Test Cricket. *Journal of Strength and Conditioning Research*, 25(5), 1368–1373.

Pietrzak, R. H., Cohen, H., & Snyder, P. J. (2007). Spatial learning efficiency and error monitoring in normal aging: An investigation using a novel hidden maze learning test. *Archives of Clinical Neuropsychology*, 22(2), 235–245.

Pietrzak, R. H., Maruff, P., Mayes, L. C., Roman, S. A., Sosa, J. A., & Snyder, P. J. (2008). An examination of the construct validity and factor structure of the Groton Maze Learning Test, a new measure of spatial working memory, learning efficiency, and error monitoring. *Archives of Clinical Neuropsychology*, 23(4), 433–445.

Pinniger, G. J., Steele, J. R., & Groeller, H. (1999). Does fatigue induced by repeated dynamic efforts affect hamstring muscle function? *Medicine & Science in Sports & Exercise*, 647–653.

Pote, L. (2013). Selected Physiological and Perceptual Responses of Batsmen During a Simulated One Day International Century: Impact on Performance. *Unpublished Masters Thesis.* Rhodes University.

Pote, L., & Christie, C. J. (2015). Selected physiological and perceptual responses during a simulated limited overs century in non-elite batsmen. *European Journal of Sports Science*, 1391(June).

Pote, L., & Christie, C. J. (2016). Physiological responses of batsmen during a simulated One Day International century. *South African Journal of Sports Medicine*, 28(2), 5–8.

Presland, J. D., Dowson, M. N., & Cairns, S. P. (2005). Changes of motor drive, cortical arousal and perceived exertion following prolonged cycling to exhaustion. *European Journal of Applied Physiology*, 95(1), 42–51.

Prinsloo, G. E., Rauch, H. G. L., Lambert, M. I., Muench, F., Noakes, T. D., & Derman, W. E. (2011). The effect of short duration heart rate variability (HRV) biofeedback on cognitive performance during laboratory induced cognitive stress. *Applied Cognitive Psychology*, 25(5), 792–801.

Purves, D., Augustine, G. J., Fitzpatrick, D., Katz, L. C., LaMantia, A. S., McNamara, J. O., & Williams, M. S. (2004). *Neuroscience* (3rd ed.). Sunderland (MA): Sinauer Associates, Inc.

Regan, D. (1997). Visual factors in hitting and catching. *Journal of Sports Sciences*, 15(6), 533–58.

Repovs, G., & Baddeley, A. D. (2006). The multi-component model of working memory: Explorations in experimental cognitive psychology. *Neuroscience*, 139(1), 5–21.

Reyes del Paso, G. A., Langewitz, W., Mulder, L. J. M., van Roon, A., & Duschek, S. (2013). The utility of low frequency heart rate variability as an index of sympathetic cardiac tone: A review with emphasis on a reanalysis of previous studies. *Psychophysiology*, 50(5), 477–487.

Ripoll, H., Kerlirzin, Y., Stein, J. F., & Reine, B. (1995). Analysis of information processing, decision making, and visual strategies in complex problem solving sport situations. *Human Movement Science*, 14, 325–349.

Robert, G., & Hockey, J. (1997). Compensatory control in the regulation of human performance under stress and high workload: A cognitive-energetical framework. *Biological Psychology*, 45(1–3), 73–93.

Robineau, J., Jouaux, T., Lacroix, M., & Babault, N. (2012). Neuromuscular fatigue induced by a 90-minute soccer gaming modelling. *Journal of Strength and Conditioning Research*, 26(2), 555–562.

Roca, A., Ford, P. R., McRobert, A. P., & Williams, A. M. (2011). Identifying the processes underpinning anticipation and decision-making in a dynamic time-constrained task. *Cognitive Processing*, (12), 301–310.

Sarpeshkar, V., & Mann, D. L. (2011). Biomechanics and visual-motor control: how it has, is, and will be used to reveal the secrets of hitting a cricket ball. *Sports Biomechanics*, 10(4), 306–323.

Sarter, M., Givens, B., & Bruno, J. P. (2001). The cognitive neuroscience of sustained attention: Where top-down meets bottom-up. *Brain Research Reviews*, 35(2), 146–160.

Seidel, R. J., Perencevich, K. C., & Kett, A. L. (2005). Psychomotor Domain. In *From Principles of Learning to Strategies for Instruction*. New York, NY.: Springer.

Serwah, N., & Marino, F. E. (2006). The combined effects of hydration and exercise heat stress on choice reaction time. *Journal of Science and Medicine in Sport*, 9(1–2), 157–164.

Sheppard, B. J. (2011). Musculoskeletal and Perceptual Responses of Batsmen Comparing High- and Moderate-Volume Sprints Between the Wickets. *Unpublished Masters Thesis.* Rhodes University.

Sibley, B. A., Etnier, J. L., & Le Masurier, G. C. (2006). Effects of an Acute Bout of Exercise on Cognitive Aspects of Stroop Performance. *Journal of Sport & Exercise Psychology*, 28, 285–299.

Skurvydas, A., Brazaitis, M., Andrejeva, J., Mickeviciene, D., & Streckis, V. (2011). The effect of multiple sclerosis and gender on central and peripheral fatigue during 2-min MVC. Clinical Neurophysiology, 122(4), 767–76.

Slogrove, L., Potgieter, J. R., & Foxcroft, C. D. (2002). Batting related experiences of South African University cricketers. *South African Journal for Research in Sport, Physical Education and Recreation*, 24(1), 101–111.

Smith, M. R., Newell, A. J., & Baker, M. R. (2012). Effect of acute mild dehydration on cognitive-motor performance in golf. *Journal of Strength and Conditioning Research*, 26(11), 3075–3080.

Smith, P. J., Blumenthal, J. A., Hoffman, B. M., Cooper, H., Strauman, T. A., Welsh-Bohmer, K., ... Sherwood, A. (2010). Aerobic exercise and neurocognitive performance: a meta-analytic review of randomized controlled trials. *Psychosomatic Medicine*, 72(3), 239–52.

Smits, B. L. M., Pepping, G. J., & Hettinga, F. J. (2014). Pacing and decision making in sport and exercise: The roles of perception and action in the regulation of exercise intensity. *Sports Medicine*, 44(6), 763–775.

Soga, K., Shishido, T., & Nagatomi, R. (2015). Executive function during and after acute moderate aerobic exercise in adolescents. *Psychology of Sport and Exercise*, 16(P3), 7–17.

Soo, K., & Naughton, G. (2007). The hydration profile of female cricket players during competition. *International Journal of Sport Nutrition and Exercise Metabolism*, 17(1), 14–26.

Sowell, E. R., Thompson, P. M., Holmes, C. J., Jernigan, T. L., & Toga, A. W. (1999). In vivo evidence for post-adolescent brain maturation in frontal and striatal regions. *Nature Neuroscience*, 2(10), 859–861.

Staal, M. A. (2004). *Stress, Cognition, and Human Performance: A Literature Review and Conceptual Framework*. Moffett Field, California.

St Clair Gibson, A., Baden, D., Lambert, M. I., Lambert, E. V, Harley, Y. X. R., Hampson, D., ... Noakes, T. D. (2003). The conscious perception of the sensation of fatigue. *Sports Medicine*, 33(3), 167–76.

St Clair Gibson, A., & Noakes, T. D. (2004). Evidence for complex system integration and dynamic neural regulation of skeletal muscle recruitment during exercise in humans. *British Journal of Sports Medicine*, 38, 797–807.

Stein, P. K., Bosner, M. S., Kleiger, R. E., & Conger, B. M. (1994). Heart rate variability: A measure of cardiac autonomic tone. *American Heart Journal*, 127, 1367–1381.

Steinberg, S. I., Sammel, M. D., Harel, B. T., Schembri, A., Policastro, C., Bogner, H. R., ... Arnold, S. E. (2014). Exercise, Sedentary Pastimes, and Cognitive Performance in Healthy Older Adults. *American Journal of Alzheimer's Disease and Other Dementias*, 1-9.

Sternberg, R. J., & Sternberg, K. (2012). *Cognitive Psychology*. Wadswort, Cengage Learning.

Stretch, R. A., Barnard, G., & Nurick, G. N. (2002). Improving the accuracy and consistency of stroke reproduction through a vision training programmes. *The South African Optometrist*, 61(4), 145–150.

Stretch, R. A., Bartlett, R. M., & Davids, K. (2000). A review of batting in men's cricket. *Journal of Sports Sciences*, 18(12), 931–49.

Stretch, R. A., Buys, F., Toit, E. Du, & Viljoen, G. (1998). Kinematics and kinetics of the drive off the front foot in cricket batting. *Journal of Sports Sciences*, *16*, 711–720.

Stretch, R. A., Nurick, G. N., Balden, V., & McKellar, D. M. (2004). The position of impact of a ball striking a cricket bat: assisting coaches with performance analysis of cricket technique and skill levels. *International Journal of Performance Analysis in Sport*, 4(2), 74–81.

Stretch, R. A., Nurick, G. N., & McKellar, D. M. (1999). Improving the accuracy and consistency of shot reproduction in cricket batting. *South African Journal for Research in Sport, Physical Education and Recreation*, 21(2), 77–88.

Taelman, J., Vandeput, S., Vlemincx, E., Spaepen, A., & Van Huffel, S. (2011). Instantaneous changes in heart rate regulation due to mental load in simulated office work. *European Journal of Applied Physiology*, 111(7), 1497–1505.

Taliep, M. S., St Clair Gibson, A., Gray, J., Van Der Merwe, L., Vaughan, C. L., Noakes, T. D., ... John, L. (2008). Event-related potentials, reaction time, and response selection of skilled and less-skilled cricket batsmen. *Perception*, *37*(1), 96–105.

Taliep, M. S., Prim, S. K., & Gray, J. (2010). Upper body muscle strength and batting performance in cricket batsmen. *Journal of Strength and Conditioning Research / National Strength & Conditioning Association*, *24*(12), 3484–3487.

Taliep, M. S., & John, L. (2014). Sport expertise: The role of precise timing of verbal-analytical engagement and the ability to detect visual cues. *Perception*, *43*(4), 316–332.

Teffer, K., & Semendeferi, K. (2012). Human prefrontal cortex. Evolution, development, and pathology. *Progress in Brain Research*, 195, 191.

Tharp, V. K., Rundell, O. H., Lester, B. K., & Williams, H. L. (1974). Alcohol and information processing. *Psychopharmacologia*, 40(1), 33–52.

Thayer, J. F., Hansen, A. L., Saus-Rose, E., & Johnsen, B. H. (2009). Heart rate variability, prefrontal neural function, and cognitive performance: The neurovisceral integration perspective on self-regulation, adaptation, and health. *Annals of Behavioral Medicine*, 37(2), 141–153.

Thelwell, R. C., Weston, N. J. V, & Greenlees, I. A. (2007). Batting on a sticky wicket: Identifying sources of stress and associated coping strategies for professional cricket batsmen. *Psychology of Sport and Exercise*, 8(2), 219–232.

Thibodeau, G. A., & Patton, K. T. (1999). *Anatomy and Physiology*. (J. Thompson, Ed.) (4th ed.). St. Louis, Missouri.: Mosby, Inc.

Thiffault, P., & Bergeron, J. (2003). Fatigue and individual differences in monotonous simulated driving. *Personality and Individual Differences*, 34(1), 159–176.

Tomporowski, P. D. (2003). Effects of acute bouts of exercise on cognition. *Acta Psychologica*, 112(3), 297–324.

Tomporowski, P. D., Cureton, K., Armstrong, L. E., Kane, G. M., Sparling, P. B., & Millard-Stafford, M. (2005). Short-term effects of aerobic exercise on executive processes and emotional reactivity. *International Journal of Sport and Exercise Psychology*, 3(2), 131–146.

Tomporowski, P. D., & Ellis, N. R. (1986). Effects of exercise on cognitive processes: A review. *Psychological Bulletin*, 99(3), 338–346.

Tomporowski, P. D., & Ganio, M. S. (2006). Short-term effects of aerobic exercise on executive processing, memory, and emotional reactivity. *International Journal of Sport and Exercise Psychology*, 4(1), 57–72.

Tortora, G. J., & Derrickson, B. H. (2005). *Principles of Anatomy and Physiology*. (B. Roesch, Ed.) (11th ed.). Hoboken, NJ.: John Wiley and Sons, Inc.

Trimmel, K., Sacha, J., & Huikuri, H. V. (2015). *Heart Rate Variability: Clinical Applications and Interaction between HRV and Heart Rate*. Lausanne: Frontiers Media.

Tucker, R. (2009). The anticipatory regulation of performance: the physiological basis for pacing strategies and the development of a perception-based model for exercise performance. *British Journal of Sports Medicine*, 43, 392–400.

Tucker, R., & Noakes, T. D. (2009). The physiological regulation of pacing strategy during exercise: a critical review. *British Journal of Sports Medicine*, 43(6), 1–9.

Ulmer, H. V. (1996). Concept of an extracellular regulation of muscular metabolic rate during heavy exercise in humans by psychophysiological feedback. *Experientia*, 52(5), 416–420.

Underwood, B. J. (2016). Memory. In *Encyclopaedia Britannica*. Retrieved from http://global.britannica.com/topic/memory-psychology.

Van Duinen, H., Lorist, M. M., & Zijdewind, I. (2005). The effect of caffeine on cognitive task performance and motor fatigue. *Psychopharmacology*, 180(3), 539–547.

Vickery, W. M. (2014). The Use of Game-Based Training to Provide a Match- Specific Environment for Cricket Players Statement of Originality. *Unpublished Doctoral Dissertation.* The University of Newcastle.

Vickery, W. M., Dascombe, B., & Duffield, R. (2014). Physiological, movement and technical demands of centre-wicket Battlezone, traditional net-based training and one-day cricket matches: a comparative study of sub-elite cricket players. *Journal of Sports Sciences*, 32(8), 722–37.

Vickery, W. M., Dascombe, B., Duffield, R., Kellett, A., & Portus, M. R. (2013a). Battlezone: An examination of the physiological responses, movement demands and reproducibility of small-sided cricket games. *Journal of Sports Sciences*, 31(1), 77–86.

Vickery, W. M., Dascombe, B., Duffield, R., Kellett, A., & Portus, M. R. (2013b). The influence of field size, player number and rule changes on the physiological responses and movement demands of small-sided games for cricket training. *Journal of Sports Sciences*, 31(6), 629–38.

Vohs, K. D., & Heatherton, T. F. (2000). Self-Regulatory Failure: A Resource-Depletion Approach. *Psychological Science*, 11(3), 249–254.

Weissensteiner, J., Abernethy, B., Farrow, D., & Müller, S. (2008). The Development of Anticipation: A Cross-Sectional Examination of the Practice Experiences Contributing to Skill in Cricket Batting. *Journal of Sport & Exercise Psychology*, 30(6), 663–684.

Welsh, R. S., Davis, J. M., Burke, J. R., & Williams, H. G. (2002). Carbohydrates and physical/mental performance during intermittent exercise to fatigue. *Medicine & Science in Sports & Exercise*, 34(4), 723–31.

Wickens, C. D. (1984). *Processing resources in attention. Varieties of attention.* (R. Parasurama & R. Davies, Eds.). New York, NY.: Academic Press.

Wickens, C. D. (2002). Multiple resources and performance prediction. *Theoretical Issues in Ergonomics Science*, 3(2), 159–177.

Wickens, C. D. (2008). Multiple Resources and Mental Workload. *Human Factors*, 50(3), 449–455.

Wickens, C. D., & Hollands, J. G. (2000). *Engineering Psychology and Human Performance*. New Jersey. Prentice-Hall Inc.

Wickens, C. D., & Kramer, A. (1985). Engineering Psychology. *Annual Review of Psychology*, 36, 307–348.

Wickens, C. D., Mavor, A. S., & McGee, J. P. (1997). *Flight to the future: Human factors in air traffic control*. Washington DC. National Academy Press.

Wolpert, D. M., Ghahramani, Z., & Flanagan, J. R. (2001). Perspectives and problems in motor learning. *Trends in Cognitive Sciences*, *5*(11), 487–494.

Woolmer, B., Noakes, T. D., & Moffett, H. (2008). *Bob Woolmer's Art and Science of Cricket*. Struik.

Xhyheri, B., Manfrini, O., Mazzolini, M., Pizzi, C., & Bugiardini, R. (2012). Heart Rate Variability Today. *Progress in Cardiovascular Diseases*, 55(3), 321–331.

Yanagisawa, H., Dan, I., Tsuzuki, D., Kato, M., Okamoto, M., Kyutoku, Y., & Soya, H. (2010). Acute moderate exercise elicits increased dorsolateral prefrontal activation and improves cognitive performance with Stroop test. *NeuroImage*, 50(4), 1702–1710.

Yerkes, R. M., & Dodson, J. D. (1908). The relation of strength of stimulus to rapidity of habit-formation. *Journal of Comparative Neurology and Psychology*, 18(5), 459–482.

Young, M. S., & Stanton, N. A. (2002a). Attention and automation: New perspectives on mental underload and performance. *Theoretical Issues in Ergonomics Science*, 3(2), 178–194.

Young, M. S., & Stanton, N. A. (2002b). Malleable attentional resources theory: a new explanation for the effects of mental underload on performance. *Human Factors*, 44(3), 365–375.

Zois, J., Bishop, D. J., Ball, K., & Aughey, R. J. (2011). High-intensity warm-ups elicit superior performance to a current soccer warm-up routine. *Journal of Science and Medicine in Sport*, 14(6), 522–528.

APPENDICES

10.1 Appendix A: Dissertation-based Research Outputs

10.1.1 Peer Reviewed Publications

10.2 Appendix B: General Information

10.2.1 Letter of Ethics Approval

10.2.2 Letter of Information to Participants (Phase 1)

10.2.3 Letter of Information to Participants (Phase 2 & 3)

10.2.4 Consent Forms

10.3 Appendix C: Data Collection

10.3.1 Pre-Test Instructions

10.3.2 Demographic Data Collection Forms

10.3.3 Data Collection Forms: Phase 1

10.3.4 Data Collection Forms: Phase 2 & 3

JOURNAL OF SPORTS SCIENCES, 2016
http://dx.doi.org/10.1080/02640414.2016.1211731

Routledge
Taylor & Francis Group

Cognitive, physical and physiological responses of school boy cricketers to a 30-over batting simulation

David Goble and Candice Jo-Anne Christie

Department of Human Kinetics and Ergonomics, Rhodes University, Grahamstown, South Africa

ABSTRACT

The purpose of this study was to assess how cognitive and physical performance are affected during a prolonged, fatigue-inducing cricket-batting simulation. Fifteen amateur batters from three Eastern Cape schools in South Africa were recruited (mean ± SD: age 17 ± 0.92 years; stature 1.75 ± 0.07 m; body mass 78.3 ± 13.2 kg). Participants completed a 6-stage, 30-over batting simulation (BATEX©). During the protocol, there were five periods of cognitive assessment (CogState brief test battery, Melbourne, Australia). The primary outcome measures from each cognitive task were speed and accuracy/error rates. Physiological (heart rate) and physical (sprint times) responses were also recorded. Sprint times deteriorated ($d = 0.84$; $P < 0.01$) while physiological responses increased ($d = 0.91$; $P < 0.01$) as batting duration increased, with longest times and highest responses occurring in the final stage. Prolonged batting had a large effect on executive task performance ($d = 0.85$; $P = 0.03$), and moderate effects on visual attention and vigilance ($d = 0.56$; $P = 0.21$) and attention and working memory ($d = 0.61$; $P = 0.11$), reducing task performance after 30 overs. Therefore, prolonged batting with repeated shuttle running fatigues amateur batters and adversely affects higher-order cognitive function. This will affect decision-making, response selection, response execution and other batting-related executive processes. We recommend that training should incorporate greater proportions of centre-wicket batting with repeated, high-intensity shuttle running. This will improve batting-related skills and information processing when fatigued, making practice more representative of competition.

ARTICLE HISTORY
Accepted 5 July 2016

KEYWORDS
Batting; fatigue; cognition; performance; CogState

Introduction

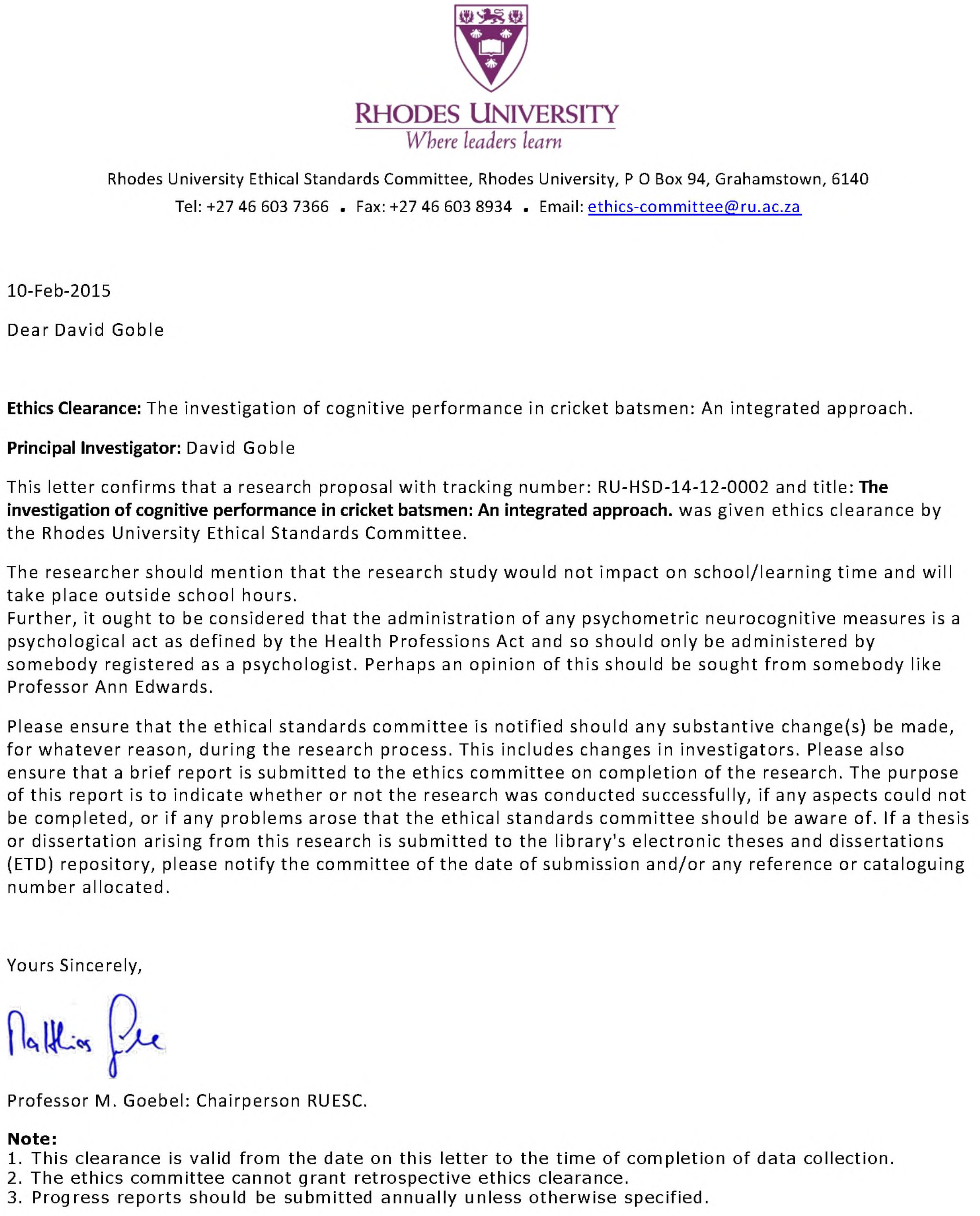
Batting in cricket is physiologically demanding (Christie & Pote, 2014; Johnstone & Ford, 2010; King, Christie, & Todd, 2002), resulting in fatigue (Christie, Todd, & King, 2008; Houghton, Dawson, Rubenson, & Tobin, 2011b; Noakes & Durandt, 2000) that adversely affects sprint performance (Houghton, Dawson, & Rubenson, 2011a; Vickery, Dascombe, & Duffield, 2014). Batting is also mentally demanding (Houghton et al., 2011b; Noakes & Durandt, 2000) as it requires accurate and rapid decision-making and sustained attention (Neave et al., 2004). No study has attempted to quantify the cognitive demands of prolonged batting or link this with physical effort and fatigue. This is largely because of the complex nature of cognitive assessment and the difficulty in replicating match play and hence, competition pressures of cricket.

Successful interception of a cricket ball involves a series of behaviours/information processing sequences: identification of fielding positions and gaps in the field, determination of ball position in the bowler's hand, assessment of ball-release height and ball trajectory and shot selection and execution. When facing delivery of ball speeds between 120 and 150 $\text{km} \cdot \text{h}^{-1}$ batters must complete this sequence in approximately 425–530 ms (from ball release to shot execution) to successfully intercept the ball. Further, the time between ball bounce and arrival at the batter is approximately 200 ms (Land & McLeod, 2000). For successful shot selection and execution under these time constraints, batters require heightened focus and selective attention. When these actions are consistently repeated and combined with prolonged physical activity, it is likely that fatigue will result. This could reduce batters' ability to successfully intercept the ball.

However, physical fatigue is not the sole reason this happens. A complex series of interactions can influence batters' success. It is these interactions that make the assessment of batting performance difficult. The dynamic nature of cricket is one of the major constraints in assessing performance. Batters consistently have to modify information processing sequences to adapt to the associated challenges (e.g., bowling changes, fielding changes, match states and physical fatigue). Distraction by opponents, crowd dynamics, previous performances as well as batting psychology can also influence batters' focus. Attention is further affected by match status, e.g., runs needed to win, information from coaching staff, personal factors and other extraneous variables (the umpire's decision). Relatedly, each of these factors in isolation could lead to a batter failing (i.e., getting out). Replication of match demands and intensities in laboratory settings are other factors that complicate assessment. For these reasons, assessment of factors that underpin batting performance is challenging and hence,

CONTACT David Goble g07g2728@campus.ru.ac.za; davegoble87@gmail.com

Letter of Ethics Approval



RHODES UNIVERSITY
Where leaders learn

Rhodes University Ethical Standards Committee, Rhodes University, P O Box 94, Grahamstown, 6140
Tel: +27 46 603 7366 • Fax: +27 46 603 8934 • Email: ethics-committee@ru.ac.za

10-Feb-2015

Dear David Goble

Ethics Clearance: The investigation of cognitive performance in cricket batsmen: An integrated approach.

Principal Investigator: David Goble

This letter confirms that a research proposal with tracking number: RU-HSD-14-12-0002 and title: **The investigation of cognitive performance in cricket batsmen: An integrated approach.** was given ethics clearance by the Rhodes University Ethical Standards Committee.

The researcher should mention that the research study would not impact on school/learning time and will take place outside school hours.
Further, it ought to be considered that the administration of any psychometric neurocognitive measures is a psychological act as defined by the Health Professions Act and so should only be administered by somebody registered as a psychologist. Perhaps an opinion of this should be sought from somebody like Professor Ann Edwards.

Please ensure that the ethical standards committee is notified should any substantive change(s) be made, for whatever reason, during the research process. This includes changes in investigators. Please also ensure that a brief report is submitted to the ethics committee on completion of the research. The purpose of this report is to indicate whether or not the research was conducted successfully, if any aspects could not be completed, or if any problems arose that the ethical standards committee should be aware of. If a thesis or dissertation arising from this research is submitted to the library's electronic theses and dissertations (ETD) repository, please notify the committee of the date of submission and/or any reference or cataloguing number allocated.

Yours Sincerely,

Professor M. Goebel: Chairperson RUESC.

Note:
1. This clearance is valid from the date on this letter to the time of completion of data collection.
2. The ethics committee cannot grant retrospective ethics clearance.
3. Progress reports should be submitted annually unless otherwise specified.

Letter of Information to Participants (*Phase 1*)

Principal Researcher
David Goble
PhD Scholar
Mobile: 072 225 6909
g07g2728@campus.ru.ac.za

To whom it may concern

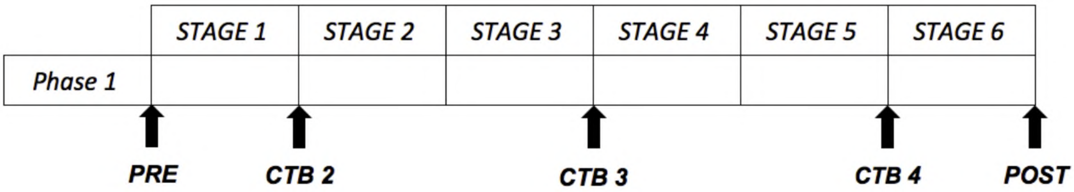
Firstly thank you for participating in the current study entitled, "**The investigation of cognitive performance in cricket batsmen: An integrated approach**", your time and efforts are greatly appreciated. The aim of the current investigation is to determine cognitive performance during a 30-over simulated batting protocol, where the reliability and validity of the cognitive test battery that will also be assessed. This letter serves to inform you of the aims and objects of the study as well as to educate you as to what is exactly required of you. Participation in this study will require you to attend two sessions. The first is an introductory session and the second, the experimental session.

Introductory session

The requirements in this initial session are minimal, and acts purely as a basis for me to explain the protocol and to obtain certain anthropometric, morphological and demographic characteristics from you. An explanation of the testing procedure and what the study aims to achieve will be given to you. Following this explanation I will ask you if you consent to participate, thereafter I will require you to sign a consent form. The session will require 40 min of your time and I will conduct the following measures with you, stature and mass (anthropometric), skin fold analysis (morphological) age, ethnicity, player history and other cricket-specific information (demographic). Once these measures are complete, I will introduce you to the cognitive test battery that you will be completing in the experimental session, you will be required to complete the entire 18 minute protocol, after which I will ask you a series of questions to gauge your understanding of each task. You should note that your participation is voluntary and if at any stage you feel you do not want to continue the experiment, you may withdraw your participation.

Experimental session

This stage of the investigation requires one session that will be physically and cognitively demanding for you, where you will be required to complete and achieve certain goal-directed cricket outcomes. Experimentation will involve five sets of cognitive test batteries (exactly the same as the one you complete in the introductory session), interspersed by six periods of batting. In total you will be batting for 30 overs (six stages of five overs) in full protective cricket kit against a bowling machine set at 105 $km.h^{-1}$. Each stage requires a different intensity and number of runs that you will need to complete. Running will be carried out in shuttles along a demarcated pitch 17.68 m in length in the following formats; ones (single shuttle), two's (double shuttle), threes (triple shuttle) and fours (one and a half shuttles). Cognitive assessment will take place before the start of batting (CTB1) and after the following stages 1, 3, 5 and 6 (CTB2-5). It is very important that you perform each test to the best of your ability, performing them as fast as you can and as accurately as possible – these are after all performance tests. The following table outlines the test protocol (total duration of the protocol will be 3 hrs 40 min).



From the above experimentation I will be measuring the following performance variables; physical performance (sprint times and batting accuracy), physiological responses (heart rate and heart rate variability) and cognitive performance (psychomotor function, visual attention, vigilance, visual learning & memory as well as attention and working memory). Please note that none of the equipment in the current study is invasive.

Upon completion of the experimentation and interpretation, I will willingly discuss the results of my project with you, thereby sharing the knowledge gained with you, the participant. Please note that any information obtained in both sessions will be kept confidential and at no stage or time will any of your personal information be used or publicised. The data that will be collected during the testing protocol will be used only for statistical analysis. All data that is measured will be given a unique code, negating the use of names and ensuring anonymity. This data will be kept for a period of five years, thereafter it will be discarded.

Moreover one copy of the data will be kept in the Human Kinetics and Ergonomics department and may be used for teaching or research purposes, however anonymity is still insured.

If at any time that you feel you cannot continue with the protocol, please feel free to withdraw from the protocol. Furthermore should you feel you cannot continue with the study, you may by all means withdraw at any time, this will not result in you being questioned for any reason. If there are any queries that you may have, feel free to contact me in the Human Kinetics and Ergonomics department. Further, should you feel that you have been mistreated in any way, please feel free to contact a neutral party at the Department of Human Kinetics and Ergonomics on the details below. I would like to thank you for your participation in my doctoral research, your help as a participant is greatly appreciated.

Yours sincerely

David Goble

Departmental details
Tel: (046) 603 8471
Fax: (046) 603 8934
jmcdougall@ru.ac.za (secretary)

Letter of Information to Participants (*Phase 2 & 3*)

Principal Researcher
David Goble
PhD Scholar
Mobile: 072 225 6909

g07g2728@campus.ru.ac.za

To whom it may concern

Firstly thank you for participating in the current study entitled, "**The investigation of cognitive performance in cricket batsmen: An integrated approach**", your time and efforts are greatly appreciated. The aim of the current research is to determine the relationship between the physiological, physical and cognitive performance responses to a 30-over simulated batting protocol. This letter serves to inform you of the aims and objects of the study as well as to educate you as to what is exactly required of you. Participation in this study will requires you to attend three sessions. The first is an introductory session and the second and third, the experimental session. You should note that your participation is voluntary and if at any stage you feel you do not want to continue with the experiment, you may withdraw your participation.

Introductory session (60 minutes)

The requirements in this initial session are minimal, and acts purely as a basis for me to explain the protocol and to obtain certain anthropometric, morphological and demographic characteristics from you. An explanation of the testing procedure and what the study aims to achieve will be given to you. Following this explanation I will ask you if you consent to participate, thereafter I will require you to sign a consent form. The session will require 60 min of your time and I will conduct the following measures with you, stature and mass (anthropometric), skin fold analysis (morphological) age, ethnicity, player history and other cricket-specific information (demographic) and vertical jump performance. Once these measures are complete, I will introduce you to the cognitive test battery that you will be completing in the experimental session, you will be required to complete the battery twice, after which I will ask you a series of questions to gauge your understanding of each task.

Experimental sessions (3hrs 10mins)

This stage of the investigation requires two sessions (separated by approximately 10 days) that will be physically and cognitively demanding for you. In these sessions you will be required to complete the same goal-directed cricket outcomes. Experimentation will involve three sets of cognitive assessment (exactly the same as the one you complete in the introductory session), interspersed by two 15 over periods of batting. In total you will be batting for 30 overs (six stages of five overs) in full protective cricket kit against a bowling machine set at 105 km.h^{-1}. Each stage requires a different intensity and number of runs that you will need to complete (Table I).

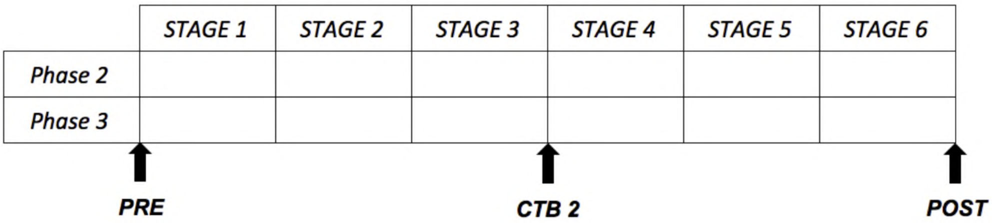
Table I: BATEX protocol (numbers indicate the type and number of shuttles required in the over. Stage 2, 4 and 6 are done at maximal intensity).

	Runs completed in each over of BATEX					**Totals**	
BATEX stages and description	**Over 1**	**Over 2**	**Over 3**	**Over 4**	**Over 5**	**Runs**	**Shuttles**
1. Building momentum	1,1	No runs	1,1,2	1,4	1,4	**16**	**9**
2. Taking initiative	1,1	1,1,2	1,1,4	1,1,2	1,1,4	**22**	**15**
3. Fighting Back	No runs	1	1,4	2,3	1,4	**16**	**9**
4. Power play	1,1,4	1,1,2	1,1,4	1,1,2,3	1,1,4	**29**	**18.5**
5. Mainitaining tempo	1,3	1,1,2	1,1,4	1,1,2	1,1,4	**24**	**17**
6. Closing out the game/innings	1,1,3,4	1,1,2,4	1,1,4,1	1,1,2	1,1,2,4	**36**	**21.5**

Overall run breakdown:	**49: 1's**	**11: 2's**	**4: 3's**	**15: 4's**	**34: Turns**	**143**	**90**

Running will be carried out in shuttles along a demarcated pitch 17.68 m in length in the following formats; ones (single shuttle), two's (double shuttle), threes (triple shuttle) and fours (one and a half shuttles). Cognitive assessment will take place before the start of batting (*pre*) after 15 overs (*during*) and after 30 overs (*post*). It is very important that you perform each test to the best of your ability, performing them as fast as you can but most importantly as accurately as possible – these are after all performance tests. Table II outlines the test protocol (total duration of the protocol will be approximately 3 hrs).

Table II: Experimental design matrix.



	STAGE 1	*STAGE 2*	*STAGE 3*	*STAGE 4*	*STAGE 5*	*STAGE 6*
Phase 2						
Phase 3						

From the above experimentation I will be measuring the following performance variables; physical performance (sprint times, batting accuracy and vertical jump height), physiological responses (heart rate, heart rate variability and ratings of perceived exertion) and cognitive performance (psychomotor function, visual attention, vigilance, visual learning & memory as well as attention and working memory). Upon completion of the experimentation and data analysis and data interpretation, I will willingly discuss the results of my project with you, thereby sharing the knowledge gained with you, the participant.

Summary of Participant Requirements

- Attend 3 sessions (one introductory and two experimental sessions)
- Sessions separated by 10 days depending on participants schedule and availability
- Habituation session = 1 hr
- Experimental sessions = 3hrs 10 min
- Full protective cricket kit and bat (bat that can be used with bowling machine)
- Reliability

Please note that any information obtained in both sessions will be kept confidential and at no stage or time will any of your personal information be used or publicised. The data that will be collected during the testing protocol will be used only for statistical analysis. All data that is measured will be given a unique code (i.e. TUKS 001/ UJ001), negating the use of names and ensuring anonymity. This data will be kept for a period of five years, thereafter it will be discarded. Moreover, one copy of the data will be kept in the Human Kinetics and Ergonomics department and may be used for teaching or research purposes, however anonymity is still insured.

If at any time that you feel you cannot continue with the protocol, please feel free to withdraw from the protocol. Furthermore should you feel you cannot continue with the study, you may by all means withdraw at any time, this will not result in you being questioned for any reason. If there are any queries that you may have, feel free to contact me. Further, should you feel that you have been mistreated in any way, please feel free to contact a neutral party at the Department of Human Kinetics and Ergonomics on the details below. I would like to thank you for your participation in my doctoral research, your help as a participant is greatly appreciated.

Yours sincerely

David Goble

Departmental details
Tel: (046) 603 8471
Fax: (046) 603 8934
jmcdougall@ru.ac.za (secretary)

Pre-Test Instructions

Please inform the researcher of any factors that you think may influence your results on the day of testing, for example if you are taking prescription medication, are asthmatic or are ill. Please note that if you are currently carry any form of injury or have any lower limb problems, as it is advised that you do not participate in the study if this is the case. In order for my results to be accurate, I require that you follow the following instructions before completing the test.

FOR 24 HOURS PRIOR TO TESTING:

DO NOT DRINK ALCOHOL

DO NOT SMOKE

DO NOT TAKE PERFORMANCE ENHANCING SUBSTANCES

DO NOT PARTICIPATE IN ANY STRENUOUS EXERCISE

DO NOT TAKE MEDICATION (painkillers, aspirin, flu tablets or over the counter medication)

TRY TO GET AT LEAST 8 HOURS OF SLEEP THE NIGHT BEFORE THE TEST

ON THE DAY OF TESTING

EAT A SUBSTANTIAL MEAL APPROXIMATELY 2 HOURS PRIOR TO TESTING BUT REFRAIN FROM EATING 1.5 HOURS PRIOR TO TESTING

COMPLETE 24-HOUR DIETARY RECALL FORM

DO NOT CONSUME ANY CAFFEINE CONTAINING DRINKS OR CHOCOLATES

DO NOT TAKE PERFORMANCE ENHANCING SUBSTANCES

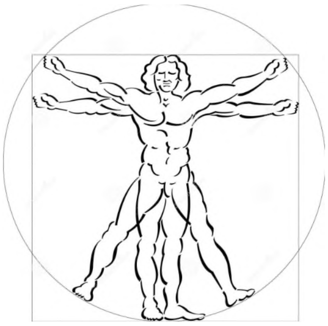
WEAR COMFORTABLE CRICKET CLOTHING THAT YOU WOULD GENERALLY WEAR DURING A MATCH

PLEASE BRING ALONG WITH YOU, A SWEAT TOWEL AND WATER BOTTLE

Please as far as you can, try to comply with the above instructions, as this will help greatly in my data collection. Your cooperation is much appreciated.

Consent Forms

Consent of Coach/School



I, ___________________________the coach of ___________________________have been fully informed of the research project entitled: "**The investigation of cognitive performance in cricket batsmen: An integrated approach"**

I am fully aware of the procedures involved as well as the potential risks and benefits attendant to the players participation as explained to me verbally and in writing. By consenting to allow players to participate in this research I accept joint responsibility together with the Human Kinetics and Ergonomics Department, in that should an accident or injury occur as a direct result of the protocol being performed during the study, the Human Kinetics and Ergonomics Department will be liable for costs which may ensue, and will reimburse the participant to the full amount, i.e. doctors' consultation, medication, rehabilitation etc. The Department will, however, waiver any legal recourse against the researcher or Rhodes University in the event the injury is self-inflicted, due to negligence of the player, or is in any other way not related directly to the study itself. I realize that it is necessary for me to promptly report to the researcher any signs or symptoms indicating any abnormality or distress on the part of the players under my supervision. I am aware that I may withdraw my consent and may withdraw any player from participation in the research at any time without consequences to the player or the school. I am also aware that the anonymity of the players will be protected at all times, and agree that the information collected may be used and published for statistical or scientific purposes.

I have read the information sheet accompanying this form and understand it. Consent is given to the researcher to conduct the explained research on Kingswood College grounds using Kingswood College facilities. Any questions which may have occurred to me have been answered to my satisfaction.

I therefore consent to voluntarily allow my player to participate in this research project.

COACH:

(Print name)	(Signed)	(Date)

PERSON ADMINISTERING INFORMED CONSENT:

(Print name)	(Signed)	(Date)

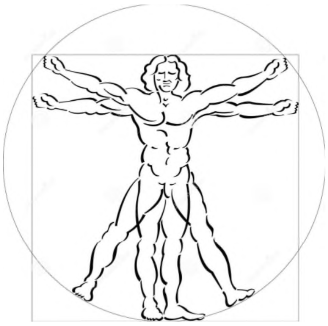
WITNESS 1:

(Print name)	(Signed)	(Date)

WITNESS 2:

(Print name)	(Signed)	(Date)

Consent of Parent/Guardian (in case for minors)



I, _______________________the parent/guardian of _______________________have been fully informed of the research project entitled: “**The investigation of cognitive performance in cricket batsmen: An integrated approach”**

I am fully aware of the procedures involved as well as the potential risks and benefits attendant to my sons participation as explained to me verbally and in writing. By consenting to my sons participation in this research I accept joint responsibility together with the Human Kinetics and Ergonomics Department, in that should an accident or injury occur as a direct result of the protocol being performed during the study, the Human Kinetics and Ergonomics Department will be liable for costs which may ensue, and will reimburse the participant to the full amount, i.e. doctors' consultation, medication, rehabilitation etc. The Department will, however, waiver any legal recourse against the researcher or Rhodes University in the event the injury is self-inflicted, due to negligence of the subject, or is in any other way not related directly to the study itself. I accept that Kingswood College, Grahamstown, South Africa will not be held liable for any loss, damage or injury that may occur on their property during testing. I realize that it is necessary for me to promptly report to the researcher any signs or symptoms indicating any abnormality or distress occurring to my son. I am aware that I may withdraw my consent and may withdraw my son from participation in the research at any time without consequences. I am also aware that my sons anonymity will be protected at all times, and agree that the information collected may be used and published for statistical or scientific purposes.

I have read and understood the above information, as well as the information provided in the letter accompanying this form.

I therefore consent to voluntarily allow my son to participate in this research project.

PARENT (LEGAL REPRESENTATIVE):

____________________ ____________________ ____________________

(Print name) (Signed) (Date)

PERSON ADMINISTERING INFORMED CONSENT:

____________________ ____________________ ____________________

(Print name) (Signed) (Date)

WITNESS 1:

____________________ ____________________ ____________________

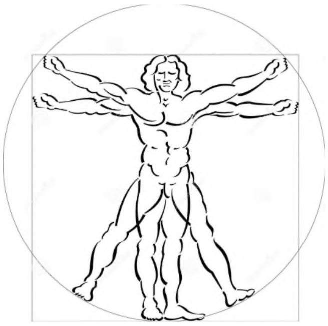
(Print name) (Signed) (Date)

WITNESS 2:

____________________ ____________________ ____________________

(Print name) (Signed) (Date)

Assent of Participant (in case for minors)



I, ______________________________ have been fully informed of the research project entitled: “**The investigation of cognitive performance in cricket batsmen: An integrated approach”**

I have read the information sheet and understand the testing procedure that will take place. I have been told about the risks as well as benefits involved, as well as what will be expected of me as a participant. I understand that all information gained from this project will be treated confidentially, that I will remain anonymous at all times and that data obtained may be used and published for statistical or scientific purposes. All testing procedures, associated risks and the benefits from partaking in this study have been verbally explained to me as well in writing. Furthermore I understand that I may withdraw from the study at any stage, and will not be questioned as to why my withdrawal took place. I have had ample opportunity to ask questions and to clarify any concerns or misunderstandings. I am satisfied that these have been answered satisfactorily.

In light of this, and in agreeing to participate in this study, I accept joint responsibility together with the Human Kinetics and Ergonomics Department, in that should any accident or injury occur as a direct result of the protocols being performed during the study, the Human Kinetics and Ergonomics Department will be liable for any costs which may ensure and will reimburse the participant to the full amount. I.e. doctor’s consultation, medication etc. The department will, however, waiver any legal recourse against the researchers of Rhodes University, from any and all claims resulting from personal injuries sustained whilst partaking in the investigation due to negligence on the part of the participant or from injuries not directly related to the study itself. This waiver shall be binding upon my heirs and personal representatives. I have read and understood the above information, as well as the information provided in the letter accompanying this form.

I therefore assent to voluntarily participate in this research project.

PARTICIPANT:

(Print name)	(Signed)	(Date)

PERSON ADMINISTERING INFORMED CONSENT:

(Print name)	(Signed)	(Date)

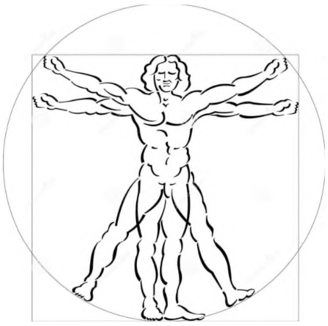
WITNESS 1:

(Print name)	(Signed)	(Date)

WITNESS 2:

(Print name)	(Signed)	(Date)

Consent Of Participant



I, ______________________________ have been fully informed of the research project entitled: “**The investigation of cognitive performance in cricket batsmen: An integrated approach**”

I have read the information sheet and understand the testing procedure that will take place. I have been told about the risks as well as benefits involved, as well as what will be expected of me as a participant. I understand that all information gained from this project will be treated confidentially, that I will remain anonymous at all times and that data obtained may be used and published for statistical or scientific purposes. All testing procedures, associated risks and the benefits from partaking in this study have been verbally explained to me as well in writing. Furthermore I understand that I may withdraw from the study at any stage, and will not be questioned as to why my withdrawal took place. I have had ample opportunity to ask questions and to clarify any concerns or misunderstandings. I am satisfied that these have been answered satisfactorily.

In light of this, and in agreeing to participate in this study, I accept joint responsibility together with the Human Kinetics and Ergonomics Department, in that should any accident or injury occur as a direct result of the protocols being performed during the study, the Human Kinetics and Ergonomics Department will be liable for any costs which may ensure and will reimburse the participant to the full amount. I.e. doctor’s consultation, medication etc. The department will, however, waiver any legal recourse against the researchers of Rhodes University, from any and all claims resulting from personal injuries sustained whilst partaking in the investigation due to negligence on the part of the participant or from injuries not directly related to the study itself. This waiver shall be binding upon my heirs and personal representatives. I have read and understood the above information, as well as the information provided in the letter accompanying this form.

I therefore assent to voluntarily participate in this research project.

PARTICIPANT:

(Print name)	(Signed)	(Date)

PERSON ADMINISTERING INFORMED CONSENT:

(Print name)	(Signed)	(Date)

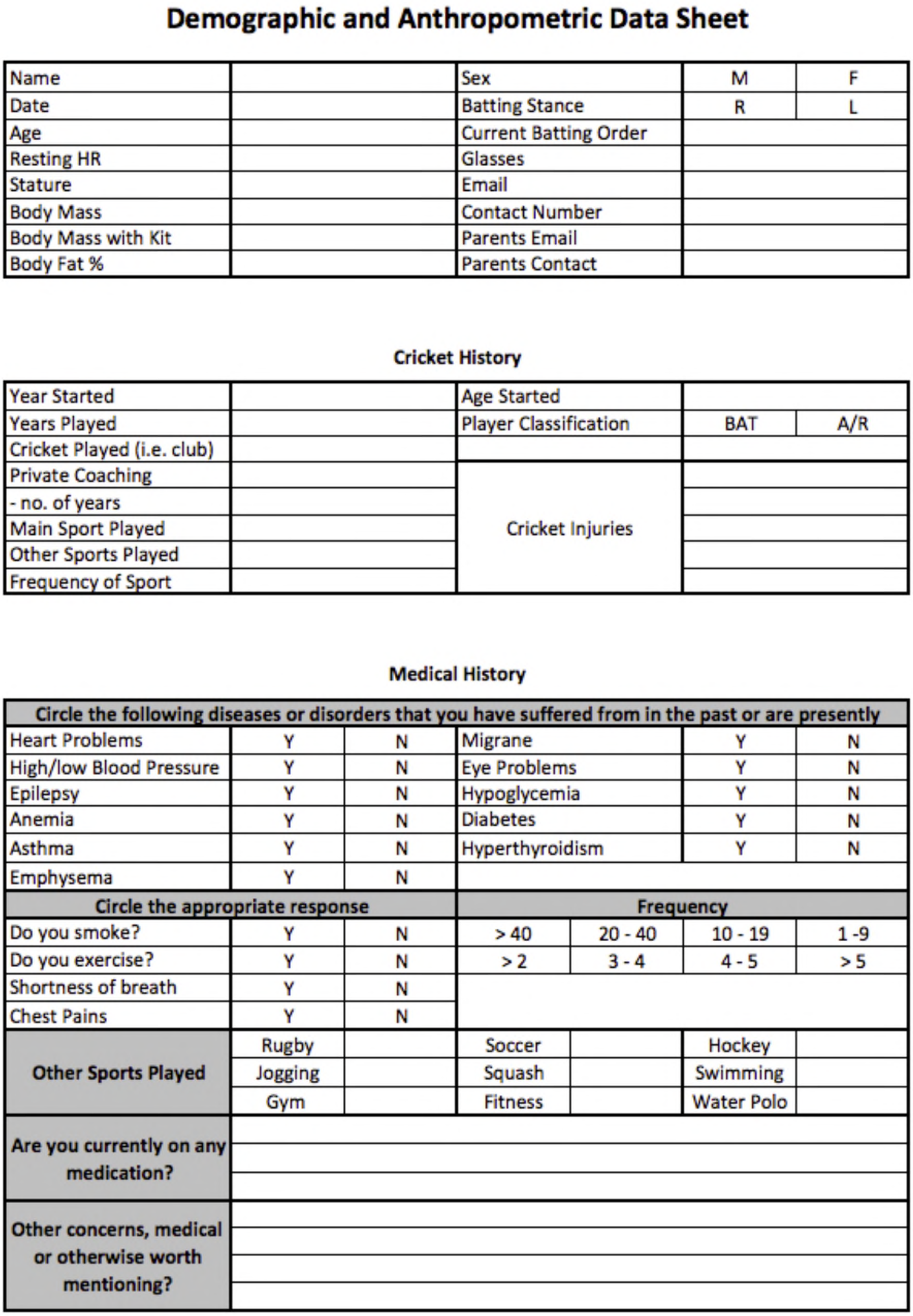
WITNESS 1:

(Print name)	(Signed)	(Date)

WITNESS 2:

(Print name)	(Signed)	(Date)

Demographic Data Collection Form



Demographic and Anthropometric Data Sheet

Name		Sex	M	F
Date		Batting Stance	R	L
Age		Current Batting Order		
Resting HR		Glasses		
Stature		Email		
Body Mass		Contact Number		
Body Mass with Kit		Parents Email		
Body Fat %		Parents Contact		

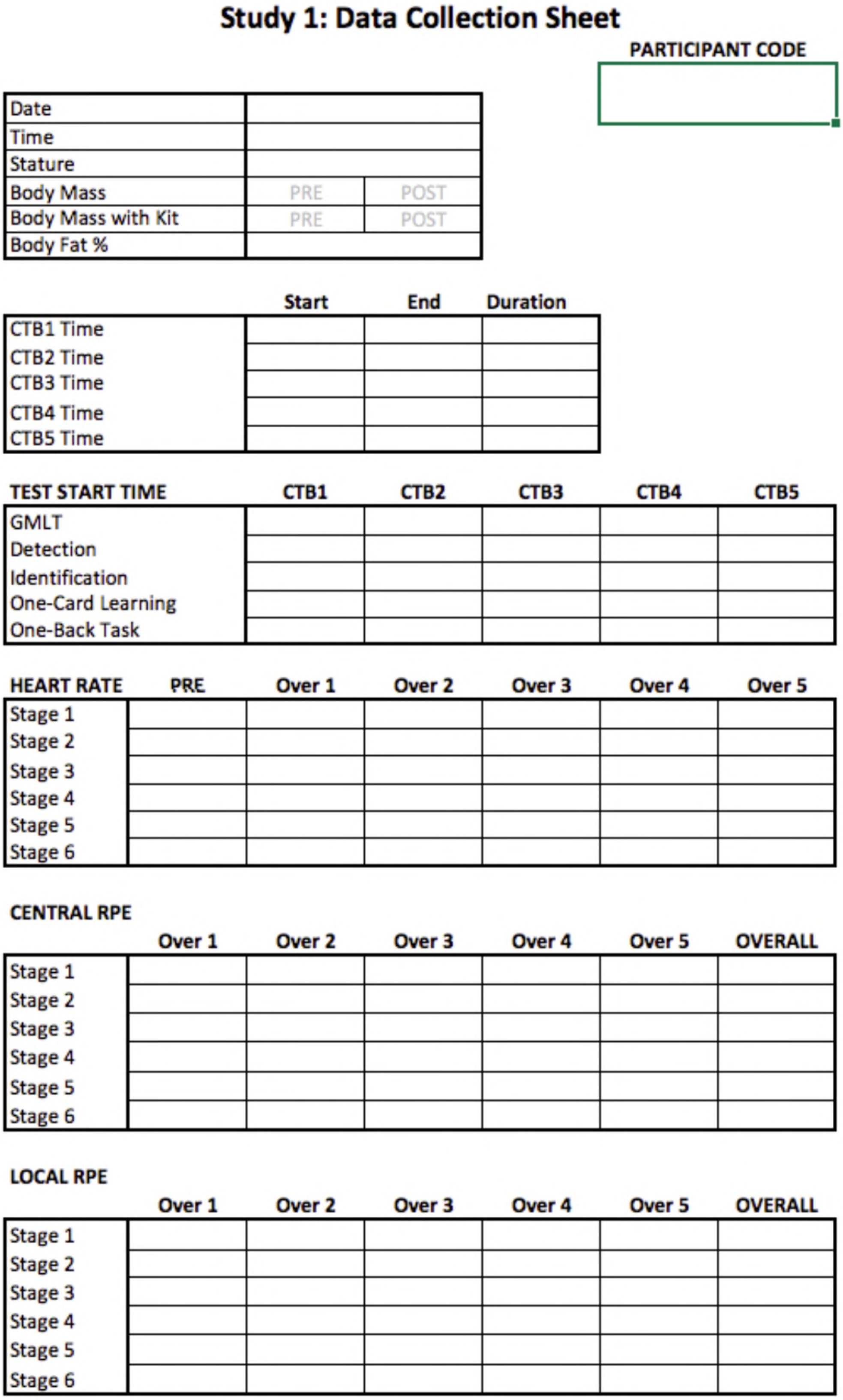
Cricket History

Year Started		Age Started		
Years Played		Player Classification	BAT	A/R
Cricket Played (i.e. club)				
Private Coaching		Cricket Injuries		
- no. of years				
Main Sport Played				
Other Sports Played				
Frequency of Sport				

Medical History

Circle the following diseases or disorders that you have suffered from in the past or are presently						
Heart Problems	Y	N	Migrane		Y	N
High/low Blood Pressure	Y	N	Eye Problems		Y	N
Epilepsy	Y	N	Hypoglycemia		Y	N
Anemia	Y	N	Diabetes		Y	N
Asthma	Y	N	Hyperthyroidism		Y	N
Emphysema	Y	N				
Circle the appropriate response			Frequency			
Do you smoke?	Y	N	> 40	20 - 40	10 - 19	1 -9
Do you exercise?	Y	N	> 2	3 - 4	4 - 5	> 5
Shortness of breath	Y	N				
Chest Pains	Y	N				
Other Sports Played	Rugby		Soccer		Hockey	
	Jogging		Squash		Swimming	
	Gym		Fitness		Water Polo	
Are you currently on any medication?						
Other concerns, medical or otherwise worth mentioning?						

Data Collection Form: *Phase 1*



Study 1: Data Collection Sheet

PARTICIPANT CODE

Date		
Time		
Stature		
Body Mass	PRE	POST
Body Mass with Kit	PRE	POST
Body Fat %		

	Start	**End**	**Duration**
CTB1 Time			
CTB2 Time			
CTB3 Time			
CTB4 Time			
CTB5 Time			

TEST START TIME	**CTB1**	**CTB2**	**CTB3**	**CTB4**	**CTB5**
GMLT					
Detection					
Identification					
One-Card Learning					
One-Back Task					

HEART RATE	**PRE**	**Over 1**	**Over 2**	**Over 3**	**Over 4**	**Over 5**
Stage 1						
Stage 2						
Stage 3						
Stage 4						
Stage 5						
Stage 6						

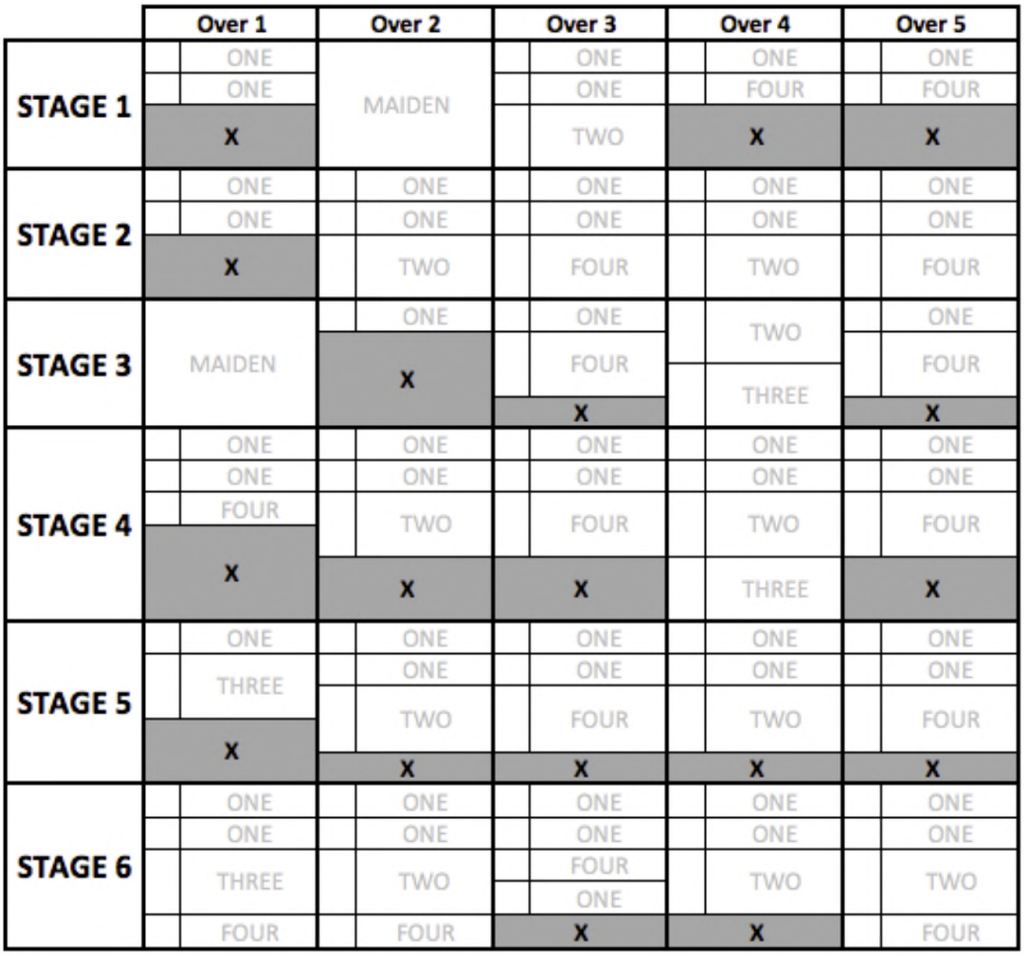
CENTRAL RPE

	Over 1	**Over 2**	**Over 3**	**Over 4**	**Over 5**	**OVERALL**
Stage 1						
Stage 2						
Stage 3						
Stage 4						
Stage 5						
Stage 6						

LOCAL RPE

	Over 1	**Over 2**	**Over 3**	**Over 4**	**Over 5**	**OVERALL**
Stage 1						
Stage 2						
Stage 3						
Stage 4						
Stage 5						
Stage 6						

SPRINT PERFORMANCE

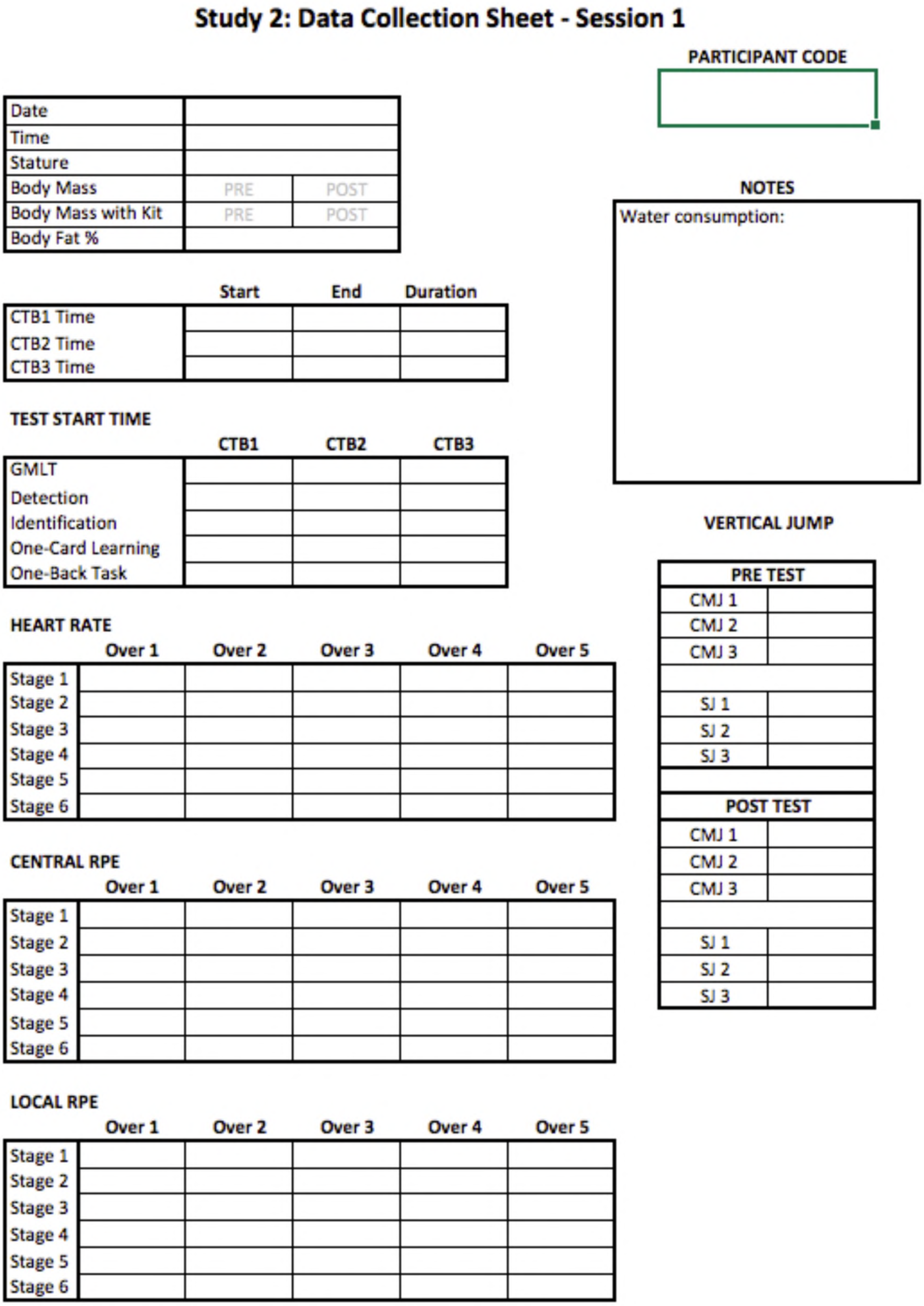


	Over 1	Over 2	Over 3	Over 4	Over 5
STAGE 1	ONE ONE X	MAIDEN	ONE ONE TWO	ONE FOUR X	ONE FOUR X
STAGE 2	ONE ONE X	ONE ONE TWO	ONE ONE FOUR	ONE ONE TWO	ONE ONE FOUR
STAGE 3	MAIDEN	ONE X	ONE FOUR X	TWO THREE	ONE FOUR X
STAGE 4	ONE ONE FOUR X	ONE ONE TWO X	ONE ONE FOUR X	ONE ONE TWO THREE	ONE ONE FOUR X
STAGE 5	ONE THREE X	ONE ONE TWO X	ONE ONE FOUR X	ONE ONE TWO X	ONE ONE FOUR X
STAGE 6	ONE ONE THREE FOUR	ONE ONE TWO FOUR	ONE ONE FOUR ONE X	ONE ONE TWO X	ONE ONE TWO FOUR

	Runs completed in each over of BATEX				
BATEX stages and description	**Over 1**	**Over 2**	**Over 3**	**Over 4**	**Over 5**
1. Building momentum	1,1	No runs	1,1,2	1,4	1,4
2. Taking initiative	1,1	1,1,2	1,1,4	1,1,2	1,1,4
3. Fighting Back	No runs	1	1,4	2,3	1,4
4. Power play	1,1,4	1,1,2	1,1,4	1,1,2,3	1,1,4
5. Mainitaining tempo	1,3	1,1,2	1,1,4	1,1,2	1,1,4
6. Closing out the game/innings	1,1,3,4	1,1,2,4	1,1,4,1	1,1,2	1,1,2,4

Overall run breakdown:	**49: 1's**	**11: 2's**	**4: 3's**	**15: 4's**	**34: Turns**

Data Collection Form: *Phase 2 & 3*



Study 2: Data Collection Sheet - Session 1

PARTICIPANT CODE

Date		
Time		
Stature		
Body Mass	PRE	POST
Body Mass with Kit	PRE	POST
Body Fat %		

NOTES

Water consumption:

	Start	End	Duration
CTB1 Time			
CTB2 Time			
CTB3 Time			

TEST START TIME

	CTB1	CTB2	CTB3
GMLT			
Detection			
Identification			
One-Card Learning			
One-Back Task			

VERTICAL JUMP

PRE TEST	
CMJ 1	
CMJ 2	
CMJ 3	
SJ 1	
SJ 2	
SJ 3	
POST TEST	
CMJ 1	
CMJ 2	
CMJ 3	
SJ 1	
SJ 2	
SJ 3	

HEART RATE

	Over 1	Over 2	Over 3	Over 4	Over 5
Stage 1					
Stage 2					
Stage 3					
Stage 4					
Stage 5					
Stage 6					

CENTRAL RPE

	Over 1	Over 2	Over 3	Over 4	Over 5
Stage 1					
Stage 2					
Stage 3					
Stage 4					
Stage 5					
Stage 6					

LOCAL RPE

	Over 1	Over 2	Over 3	Over 4	Over 5
Stage 1					
Stage 2					
Stage 3					
Stage 4					
Stage 5					
Stage 6					

Study 2: Data Collection Sheet - Session 1

SPRINT PERFORMANCE

Over 1	Over 2	Over 3	Over 4	Over 5
ONE ONE X	MAIDEN	ONE ONE TWO	ONE FOUR X	ONE FOUR X
ONE ONE X	ONE ONE TWO	ONE ONE FOUR	ONE ONE TWO	ONE ONE FOUR
MAIDEN	ONE X	ONE FOUR X	TWO THREE	ONE FOUR X
ONE ONE FOUR X	ONE ONE TWO X	ONE ONE FOUR X	ONE ONE TWO THREE	ONE ONE FOUR X
ONE THREE X	ONE ONE TWO X	ONE ONE FOUR X	ONE ONE TWO X	ONE ONE FOUR X
ONE ONE THREE FOUR	ONE ONE TWO FOUR	ONE ONE FOUR ONE X	ONE ONE TWO X	ONE ONE TWO FOUR

	Runs completed in each over of BATEX				
BATEX stages and description	**Over 1**	**Over 2**	**Over 3**	**Over 4**	**Over 5**
1. Building momentum	1,1	No runs	1,1,2	1,4	1,4
2. Taking initiative	1,1	1,1,2	1,1,4	1,1,2	1,1,4
3. Fighting Back	No runs	1	1,4	2,3	1,4
4. Power play	1,1,4	1,1,2	1,1,4	1,1,2,3	1,1,4
5. Mainitaining tempo	1,3	1,1,2	1,1,4	1,1,2	1,1,4
6. Closing out the game/innings	1,1,3,4	1,1,2,4	1,1,4,1	1,1,2	1,1,2,4

Overall run breakdown:	**49: 1's**	**11: 2's**	**4: 3's**	**15: 4's**	**34: Turns**