The Effect of Strenuous Exercise on Cognitive Function, Mood, Energy and Fatigue States in Trained Sporting Individuals

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PhD

2019

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A thesis submitted in partial fulfilment of the requirements of the University of Northumbria at Newcastle for the degree of Doctor of Philosophy

Faculty of Health and Life Sciences

December 2019

Abstract

A growing body of research has been designed to further our understanding of how single bouts of exercise affect cognitive performance. Early work in this area led to the identification of several moderating factors that influence the exercise-cognition interaction, with two of these being exercise intensity and fitness level. The positive effects of moderate-intensity are well accepted having received substantial support in the literature. Due to receiving much less attention however, there is currently no clear consensus on the effects of high-intensity exercise, though theoretical, experimental and anecdotal literature converges towards an impairment in cognitive function.

Compared to moderate intensities, strenuous exercise places much greater physiological demands on the human body and thus it has been suggested that individuals of greater fitness levels, and those accustomed to high-intensities that have undergone years of training and adaption, may respond differently to strenuous intensities compared to normal populations. Many sporting paradigms involve prolonged exercise, congested tournament fixtures and involve weeks of intensive training and thus the influence of these stressors on cognitive function and mood, energy and fatigue states in trained populations holds important implications for sports performance.

The current PhD programme aimed to examine different strenuous exercise paradigms on cognitive function, mood, energy and fatigue states in trained sporting individuals, with a particular focus on three exercise models; prolonged exercise, congested exercise and intensified training. The series of investigations that set out to address this aim have led to many novel and interesting findings. To begin, study one conducted the first systematic review in this area of the literature. Amongst highlighting the limited research, evaluation of the existing literature suggested little effect of acute strenuous exercise on measures requiring simple cognitive processing in trained populations, but found there to be more ambiguity surrounding top-down higher-order processes. This is particularly interesting, as the exercise-cognition literature has predominantly focussed on simple processes; consequently, this chapter called for the assessment of multiple cognitive domains in future studies. The first experimental study, presented in Chapter 3, examined a prolonged strenuous exercise bout on cognitive function, mood, energy and fatigue states. In support of the previous chapter's conclusions, a negative effect on executive function was found alongside reductions in mood and energy and significant increases in both physical

and mental fatigue. Building on this, Chapter 4 explored the effect of repeated strenuous exercise bouts over two days on cognitive function, mood, energy and fatigue states. Results indicated that one day of congested strenuous exercise leads to a reduction in inhibitory response accuracy and choice reaction time in addition to having negative effects on mood, energy and fatigue states. The final experimental study of this thesis, presented in Chapter 5, investigated cognitive performance, mood, energy, fatigue, perceived sleep and physical performance during and following a chronic intensified training period. This paradigm led to significant reductions in physical performance and mood during the training weeks; however, cognitive function and sleep were not affected. The practical implications of each study are discussed in each respective chapter and highlight how the results can be applied in relevant situations.

Collectively, the findings of this thesis provide novel information surrounding the effects of strenuous exercise on cognitive function, mood, energy and fatigue states in trained sporting populations. The current work has shown domain specific effects of strenuous exercise with a particular effect on top-down higher order cognitive processes. Similarly, deteriorations were observed in mood and energy states in each empirical chapter alongside significant increases in mental fatigue. Further work is required to: elucidate the mechanisms by which strenuous exercise exert these effects; to determine if these effects are observed in further exercise paradigms; and to identify methods by which cognitive function, mood, energy and fatigue states can be maintained in situations dependent upon optimal cognitive performance.

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List of abbreviations

ACC	anterior cingulate cortex
ACSM	American College of Sports Medicine
ANAM	Automated Neuropsychological Assessment Metrics
ANOVA	analysis of variance
BBB	blood-brain barrier
BDNF	brain derived neurotrophic factor
BL	baseline
bpm	beats per minute
CNS	central nervous system
CNV	contingent negative variation
COMPASS	computerised mental performance assessment system
CPT	continuous processing
CRT	choice-reaction time
CS	code substitution
CSD	code substitution delay
CV	coefficient of variation
EEG	electroencephalography
FCRT	four-choice reaction time
GPS	global position system
HIE	high-intensity exercise
HR	heart rate
HR_{av}	average heart rate
HR_{max}	heart rate maximum
HRR	heart rate reserve
ISI	Interstimulus interval
IT	intensified training
KSD	Karolinska Sleep Diary
LT	lactate threshold

MOR	μ-opioid receptors
MPO	mean power output
min	minute/s
NR	not reported
NT	normal training
pBDNF	peripheral brain derived neurotrophic factor
PFC	prefrontal cortex
POMS	Profile of Mood States
PPO	peak power output
RPE	rate of perceived exertion
RT	reaction time
SD	standard deviation
SDMT	symbol digits modality test
sec	second/s
SEM	standard error of the mean
sRPE	session rate of perceived exertion
SRT	simple reaction time
TMD	total mood disturbance
TW1	training week 1
TW2	training week 2
VAS	visual analogue scale/s
$\dot{V}O_2$	oxygen uptake
$\dot{V}O_{2max}$	maximal volume of oxygen consumption
$\dot{V}O_2R$	$\dot{V}O_2$ reserve
VSM	visuospatial memory
VT	ventilatory threshold
W	watts
WM	working memory
W_{max}	maximum aerobic power

Publications

Peer reviewed publications during the course of investigation

Browne, S.E., Flynn, M.J., O'Neill, B.V., Howatson, G., Bell, P.G. and Haskell-Ramsay, C.F. (2017) Effects of acute high-intensity exercise on cognitive performance in trained individuals: A systematic review. In *Progress in brain research* (Vol. 234, pp. 161-187). Elsevier.

Adjunct peer reviewed publications during the course of investigation

Eddens, L., **Browne, S**., Stevenson, E.J., Sanderson, B., van Someren, K. and Howatson, G., 2017. The efficacy of protein supplementation during recovery from muscle-damaging concurrent exercise. *Applied Physiology, Nutrition, and Metabolism*, 42(7), pp.716-724.

Conference communications and published abstracts during course of investigation

Browne, S.E., O'Neill, B.V., Bell, P.G., van Someren, K., Howatson, G. and Haskell-Ramsay, C.F. (2017) The effect of strenuous concurrent exercise on cognition, mood and ratings of energy and fatigue

Oral presentation, European College of Sport Science Annual Conference, 2017, Essen, Germany

Browne, S.E., O'Neill, B.V., Bell, P.G., van Someren, K., Howatson, G. and Haskell-Ramsay, C.F. (2017) The Effects of Repeated, Consecutive High-intensity Exercise on Cognitive Performance in Well-trained Team Sports Players: 847 Board# 26 May 31 2. *Medicine & Science in Sports & Exercise*, *49*(5S), pp.217-218.

Poster presentation, American College of Sports Medicine Annual Conference 2017, Denver, Colorado

Acknowledgements

The making of this thesis came with ups and downs, twists and turns and moments of self-doubt, but all of this was made so much easier by having an incredible team around me. I am very proud of this achievement, but it would not have been possible without the dedication, encouragement and support of some special people.

Firstly, I would like to thank each of my supervisors, Dr. Crystal Haskell-Ramsay, Prof. Glyn Howatson, Dr. Barry (V) O'Neill and Dr. Phill Bell. I could not have asked for a more supportive, friendly and knowledgeable team of supervisors that I now see more as friends. In the face of many hurdles and challenges, there was never a problem too big or a question too small. Thank you for your encouragement, patience, kindness, enthusiasm, and guidance, which you all effortlessly provided in abundance.

To my colleagues that I worked alongside at the GSK Human Performance Lab. What a journey that was! I feel extremely fortunate to have been afforded such a unique opportunity; it really was a dream come true. To work alongside such incredible and talented people is one thing, but to work with lifelong friends is another. Thank you for the endless laughter, support, encouragement and unforgettably outrageous outings. I would also like to specifically thank my PhD comrades – Leeroy and JJ. The chats, trips, laughs and tears; you were there through it all, thank you so much.

A special thank you to Mark Flynn, Lee Eddens and Jack Rossiter for their support in Chapters 2, 3 and 5 respectively; working with you all made this journey much more enjoyable. A big thank you also to all of the participants that contributed to this thesis; without their blood, sweat and occasional tears, there would be nothing to report.

To my mom, dad and brother. At times I'm sure it seemed that my stint as a "professional student" would never come to an end. Words cannot thank you enough for your unconditional love and support, not just throughout this PhD, but in everything I choose to do. I love you all so much, and I hope this thesis makes you proud.

Last but certainly not least, to my best friend and husband, Rogan. Your love and support knows no limits. You have moved jobs several times to support my education and without hesitation you moved countries with me to pursue my career ambitions. The late nights writing, the weekends we stayed in so I could work and the stress along the way, you have shared it all. Your strength, understanding, selflessness, encouragement and unrelenting optimism never fails to amaze me and I will be forever grateful. Thank you.

Authors declaration

I declare that the work contained in this thesis has not been submitted for any other award and that it is all my own work. I also confirm that this work fully acknowledges opinions, ideas and contributions from the work of others.

Ethical approval for the research presented in this thesis been sought and granted by the Faculty of Health and Life Sciences Ethics Committee at Northumbria University.

I declare that the word count of this thesis is 53,463 words

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Signature:

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Chapter 1: Introduction and literature review

1.1 General introduction

The past 50 years has seen a growing body of research designed to further our understanding of how acute and chronic exercise affects cognitive performance. This research is based upon the premise that physiological responses and adaptations to exercise have an impact on cognitive functioning, which can be assessed using behavioural measures. The acute physiological responses that have been implicated in the cognitive literature include; changes in heart rate (Davranche et al., 2005, Davranche et al., 2006b, Hillman et al., 2003, Kamijo et al., 2004a, Kamijo et al., 2004b), levels of brain-derived neurotrophic factor (Ferris et al., 2007, Griffin et al., 2011, Winter et al., 2007), cerebral oxygenation (Mekari et al., 2015) and changes in plasma catecholamines (Chmura et al., 1994, McMorris et al., 1999, McMorris et al., 2009). However, contradictory findings of experimental research have led to the identification of several moderating factors that influence the exercise-cognition interaction: (i) exercise intensity, (ii) exercise duration, (iii) exercise mode, (iv) cognitive task type, (v) participant fitness and (vi) timing of cognitive task administration (Brisswalter et al., 2002, Chang et al., 2012, Lambourne and Tomporowski, 2010).

The majority of research has concentrated on moderate-intensity exercise, which is generally considered to bring about positive effects in both cognition (Kashihara et al., 2009, Tomporowski, 2003) and mood (Berger and Motl, 2000, Zervas et al., 1993). Though it has received less attention, there are some suggestions that strenuous and high-intensity exercise (HIE) has the opposite effect, with reports of deteriorations in cognitive performance (Ando et al., 2005, Chmura et al., 1994, Chmura and Nazar, 2010, Cooper, 1973, Covassin et al., 2007, Dietrich, 2006, Dietrich and Audiffren, 2011, Wang et al., 2013) and mood (Berger and Motl, 2000, Hall et al., 2002). Individuals with greater fitness levels however, and athletes who are accustomed to high-training intensities and loads, may not succumb to the same detrimental effects as sedentary individuals as fitness level moderates these relationships. In line with this, there is evidence supporting superior mood effects in trained individuals following exercise compared to sedentary individuals, with this being particularly pertinent for HIE (Ekkekakis and Petruzzello, 1999).

In the world of sport, performers are faced with many challenges that place extreme demands on the brain; demands that are rarely found in any other activity (Walsh, 2014). In addition to the challenges imposed by physiological stresses associated with exercise, performers need to; process a large amount of information in a short

time under mental pressure; make fast decisions; quickly adapt; change strategy; inhibit responses; maintain spatial awareness; and predict subsequent movements (Vestberg et al., 2012). The necessary behaviour includes a creative decision-making in which both accuracy and speed are of equal importance. Such behaviour helps athletes to “read the game” and make successful a prior expectations. In addition to cognitive function, mood responses have been found to predict athletic performance and contribute to sporting success (Beedie et al., 2000) and thus the maintenance of both cognitive function and a functional mood profile is pivotal to sporting success (Knicker et al., 2011, Totterdell, 2000). This is of particular importance when training and competing in strenuous and/or stressful conditions, for example; prolonged exercise durations; congested tournament fixtures; and intensified training weeks. There is currently limited research investigating the effects of strenuous exercise on cognitive performance and mood in trained individuals. Consequently, there is an absence of information and ambiguous conclusions for athletes, coaches, sports scientists and trained populations to access and use to inform practice and potentially improve performance.

1.2 Cognitive function

Cognition is an umbrella term that includes any thought process from basic perception to action and behaviour (Erickson et al., 2012). The concept comes from the Latin word *cognoscere,* (“to know” or “to recognise”) and refers to the capacity for information processing, applying knowledge and changing preferences (Nehlig, 2010). Since the term `cognition` has been criticized for being non-specific and too inclusive (Erickson et al., 2012), it is divided into multiple domains based on the particular process or type of information being processed. Broadly speaking it involves two levels of information processing. The first level is referred to as `top down` or complex and is associated with the organisation of goal-directed actions. The second level is known as `bottom up` or simple processes and these underlie all types of complex cognition (Davis and Lambourne, 2009). In the current cognitive psychology and neuropsychology texts (Lezak, 2004, Strauss et al., 2006) cognitive function is divided into the following domains: information processing; speed of performance; attention; knowledge and expertise; executive functioning; and memory. Classifications such as this recognise the multifaceted nature of cognitive function and the necessity to examine each domain in order to accurately understand

them. This section will clearly define and describe the domains relevant to this thesis and the tasks being used to asses them.

1.2.1 Memory

Memory is a key aspect of cognitive function that includes encoding, storage and retrieval of information. Whilst being one domain of cognitive function itself, memory can be further subdivided into short-term, long-term and working memory (WM) (Nehlig, 2010). Though all are important, within sport it is generally recognised that WM and visuospatial short-term memory significantly contribute to successful sporting performance (Furley and Memmert, 2010a, Furley and Memmert, 2010b). The concept of WM was first introduced by Baddeley and Hitch (1974) in their multicomponent model and is generally described as the cognitive mechanisms capable of retaining a small amount of information in an active state for use in ongoing tasks. Visuospatial short-term memory resides within this model and describes the ability to hold and process visual and spatial information. The dynamic environment of sport requires more than the simple recall of information and thus an appropriate behavioural test should measure both concepts. The Corsi blocks task (Corsi, 1972) is one of the most widely used indexes of visuospatial memory (VSM) and is a component of major neuropsychological batteries (Kessels et al., 2008, Schuhfried, 2009) with performance being linked to a neuronal network encompassing visual occipital, posterior parietal and dorsolateral prefrontal cortices (Nemmi et al., 2013, Toepper et al., 2010).

1.2.2 Executive functions

Executive functions regulate subsidiary sensory, cognitive, emotional, and motor processes in a supervisory (or “top-down”) manner (Alvarez and Emory, 2006, Daamen and Raab, 2012). Not a cognitive domain in the strict sense, executive functioning is comprised of various “higher-level” processes that are crucial for complex decision-making and successful performance (Vestberg et al., 2012). These processes have been described as involving several functions including shifting between tasks or mental sets, updating and monitoring WM, inhibition of proponent responses, planning, and the coordination of multiple tasks (Miyake et al., 2000). Disproportional beneficial effects of acute exercise on executive functions compared with information processing, attention, and memory have recently been reported

(Chang et al., 2012). This highlights a moderating effect of specific types of cognition, suggesting that executive control may be more sensitive to acute exercise.

An important executive domain in sport is response inhibition, a main component of decision making in human volition (Haggard, 2008). A good example of response inhibition in sport would be a defender (in any sport) who refuses to respond to a `dummy` or fake action by an attacker (McMorris, 2016). The Stroop test (Stroop, 1935) is one of the most extensively used tasks to assess the ability to inhibit habitual responses as well as assessing selective attention and information processing speed (Chang and Etnier, 2009). Selective attention is the ability to concentrate on task-relevant stimuli or response options (Daamen and Raab, 2012), crucial in sport when there is irrelevant stimuli and the performer needs to select and focus on only the relevant information. Executive functions are typically associated with frontal lobe activity (Strauss et al., 2006), a region that has shown extensive synaptic connections with a broad range of cortical and subcortical structures (Daamen and Raab, 2012). A growing body of neurophysiological evidence indicates that executive domains are underpinned by different neural networks which provide separable functional outcomes (Miyake et al., 2000). Tasks involving response inhibition and selective attention are specifically known to activate the anterior cingulate cortex (ACC; located in the medial frontal lobe) which plays an important role in Stroop performance (Alvarez and Emory, 2006).

1.2.3 Reaction time

As performance in sport is reliant upon psychomotor skills, it is important to study these simpler abilities in addition to higher-order skills. The ability to maintain psychomotor skill during strenuous exercise, as is often performed in competitive sport, is crucial for good performance. Reaction time (RT) is one aspect of speed of information processing and is defined as the time elapsed between stimulus onset and the initiation of the response to it. Accordingly, it is one of the many variables involved in psychomotor skill and is a prime determinant to evaluate psychomotor performance (Ando et al., 2005). Indeed, RT is used to evaluate performance on complex tasks such as the Stroop, but there are simple RT and choice RT tasks that specifically assess psychomotor speed. Though these tasks are simple, they do involve perception to identify the stimulus and efferent organisation, albeit not very demanding organisation, to prepare the response (McMorris, 2016).

As discussed, sport is a cognitively demanding activity where successful performance execution is reliant on the constant functioning of multiple cognitive domains (Mann et al., 2007, Walsh, 2014). What's more, these actions are often performed under conditions of physiological stress and psychological stress, adding a further level of complexity and difficulty (Ando, 2016). It is thus important to examine how exercise interacts with cognitive abilities and explore the factors that can influence this complex interaction such as physical fitness, exercise intensity, exercise duration, cognitive task complexity and cognitive expertise. These factors will be discussed in detail throughout Chapter 1.

1.3 Physical fitness and exercise intensity

The term ‘physical activity’ is described as any bodily movement produced by the skeletal muscles that requires energy expenditure (Caspersen et al., 1985). Though this phrase is often used interchangeably with ‘physical exercise’, it is important to emphasise that exercise is ‘physical activity that is planned, structured, repetitive, and purposive in the sense that improvement or maintenance of one or more components of physical fitness is an objective’ (Caspersen et al., 1985). Thus, exercise is the conscious effort to improve one or more aspects of oneself. Historically, the benefits of exercise were exclusively attributed to physiological functions. More recently however, a growing body of research has been designed to further our understanding on the relationship between chronic participation in-, and acute responses to-, physical exercise on cognitive performance. In this context and throughout this thesis, acute exercise refers to that of a single bout of exercise (Chang et al., 2012), while chronic exercise refers to the repetition of exercise over time during a period lasting from weeks to years (Dietrich and Audiffren, 2011). It is important that cognitive effects following acute and chronic exercise are considered separately due to the profound influence chronic exercise training has on the structure and functions of the brain (Tomporowski et al., 2015). Changes in cognitive performance that occur during and/or following acute exercise are transient and are due to acute physiological and neurochemical changes. Changes in cognition following chronic exercise however, may also be the result of functional and structural changes in the brain.

Due to this, an important factor to consider within the exercise-cognition relationship is one’s physical fitness, which is derived from chronic exercise training. The characterisation of physical fitness and exercise intensity are discussed in the next section, followed by the influence they have on cognitive function.

1.3.1 Classification of fitness status

Physical fitness is multifaceted and encompasses multiple components including muscular endurance, strength, power, speed, agility and balance. In the exercise-cognition literature, fitness is typically expressed in terms of cardiorespiratory fitness; this involves both the circulatory and respiratory systems transporting oxygen through the body to be utilised by the working muscles for energy production, which is used to power muscular contractions (McMorris and Corbett, 2016). Oxygen uptake increases in proportion to an increase in work rate; however, if work rate continues to increase, a point will be reached where oxygen uptake plateaus and no further oxygen can be utilised. This point signifies an individual's maximal volume of oxygen consumption ($\dot{V}O_{2max}$), defined as the highest rate of which oxygen can be taken up and utilised by the body (Bassett Jr and Howley, 2000). Thus, at any given intensity individuals with greater aerobic capacities will use a lower relative percentage of their $\dot{V}O_{2max}$. Due to this, the highest aerobic capacities are often found in highly-trained endurance athletes (Bassett Jr and Howley, 2000).

$\dot{V}O_{2max}$ is considered the primary marker of cardiorespiratory fitness and is consequently used as the criterion measure to define "fitness" in exercise science research. The American College of Sports Medicine (ACSM) provide age and gender adjusted guidelines for the classification of fitness categories, which are also expressed as a percentile relative to the general population. In the most recent guidelines (Pescatello, 2014), fitness is separated into six classifications, these being: very poor, poor, fair, good, excellent and superior (Table 1.1).

Table 1.1 ACSM $\dot{V}O_{2max}$ fitness classifications for men and women aged 20-29

Fitness classification	%	Men	Women
Superior	95-99	>55.5 $ml.kg^{-1}.min^{-1}$	>49.6 $ml.kg^{-1}.min^{-1}$
Excellent	80-90	>51.1 $ml.kg^{-1}.min^{-1}$	>43.9 $ml.kg^{-1}.min^{-1}$
Good	60-75	>45.6 $ml.kg^{-1}.min^{-1}$	>39.5 $ml.kg^{-1}.min^{-1}$
Fair	40-55	>41.7 $ml.kg^{-1}.min^{-1}$	>36.1 $ml.kg^{-1}.min^{-1}$
Poor	20-35	>38.0 $ml.kg^{-1}.min^{-1}$	>32.3 $ml.kg^{-1}.min^{-1}$
Very poor	1-15	<36.7 $ml.kg^{-1}.min^{-1}$	<30.9 $ml.kg^{-1}.min^{-1}$

% = percentile relative to the general population

Whilst these provide specific guidelines, much of the literature classifies individuals as “low”, “medium” and “high” fitness relative to the participant sample. For example, Labelle et al. (2014) classified a mixed gender sample of younger adults (mean age 24.6 years) as “higher fit” with a mean $\dot{V}O_{2max}$ of 50.6 ± 7.9 $ml.kg^{-1}.min^{-1}$ and “lower fit” as 38.3 ± 5.2 $ml.kg^{-1}.min^{-1}$. Llorens et al. (2015) on the other hand classified young males (19-28 years of age) as “high-fit” with a mean $\dot{V}O_{2max}$ of 58.4 ± 3.0 $ml.kg^{-1}.min^{-1}$ and “lower fit” as 41.3 ± 6.3 $ml.kg^{-1}.min^{-1}$ while an early study by Tomporowski et al. (1987) classified a mixed-gender “high fitness” group as 66.0 $ml.kg^{-1}.min^{-1}$ and the “average fitness” as 41.1 $ml.kg^{-1}.min^{-1}$. Moreover, the standard deviation of 7.9 $ml.kg^{-1}.min^{-1}$ in the “higher fit” group in Labelle and colleagues study shows that some individuals would be well below what one might consider to be highly fit. The discrepancies in fitness classifications across studies may have led to the mixed findings on the effects of fitness on cognitive function during and following exercise. Rather than classifying participants as ‘higher-fit’ and ‘lower-fit’ individuals based on the participant sample, it is suggested that authors categorise them by the ACSM fitness classifications. Participant samples can also be compared to known aerobic fitness norms for both males and females, such as those provided by Shvartz and Reibold (1990), though an updated study is needed. Based on this study normative values suggest average young male $\dot{V}O_{2max}$ values to be around 47 $ml.kg^{-1}.min^{-1}$ while young average female $\dot{V}O_{2max}$ values are around 38 $ml.kg^{-1}.min^{-1}$. Normative values would be expected to be greater in athletic populations, particularly athletes in endurance sports (Billat et al., 2001, Legaz-Arrese et al., 2007).

1.3.2 Classification of exercise intensity

A lack of understanding of the interaction between the aerobic and anaerobic systems led early work investigating the effect of exercise on cognition to randomly select an exercise intensity for intervention. Advances in our understanding of exercise physiology has now provided evidence that physiological and biochemical changes are induced via different exercise intensities. Consequently, a large body of research has been dedicated to investigating the effect of exercise intensity on cognitive performance. However, research examining the acute exercise-cognition interaction frequently defines exercise quite broadly as low, moderate and high (also called strenuous, hard and/or heavy). This has led to many studies using different classifications of these intensities. For example, Hüttermann and Memmert (2014) describe low, moderate and high-intensity exercises as 50, 60 and 70 % of maximum

heart rate (HR_{max}) respectively, while Davranche et al. (2015) used intensities equivalent to 74, 81 and 90 % HR_{max}. Smith et al. (2016a) used 70 and 90 % heart rate reserve (HRR) as moderate and high-intensities while Wang et al. (2013) used 30 % HRR as low, 50 % as moderate and 80 % as high. Kamijo et al. (2004b) on the other hand use Borg's 6-20 rating of perceived exertion (RPE) scale to define low and moderate exercise intensities as 7-9 and 12-14 respectively, whilst high-intensity exercise was to volitional exhaustion.

As highlighted by many reviews (Brisswalter et al., 2002, Chang et al., 2012, Tomporowski and Ellis, 1986, Tomporowski, 2003), exercise intensity is a large moderating factor within the exercise-cognition relationship. Notably due to different experimental methodologies, exercise intensities have been chosen relative to different physiological markers such as $\dot{V}O_{2max}$, HR_{max}, lactate threshold (LT), RPE or percentage HRR. Though this makes comparison between studies difficult, the ACSM provide guidelines on classifications of relative intensities with comparative values across physiological markers (Table 1.2).

Table 1.2 ACSM guidelines on estimating cardiorespiratory exercise intensity

	Relative intensity			
Intensity	**% HRR or % $\dot{V}O_2R$**	**% HR maximum**	**% $\dot{V}O_{2max}$**	**RPE (6-20)**
Very light	<30	<57	<37	Very light (RPE ≤9)
Light	30 - <40	57 - <64	37 - <45	Very light to fairly light (RPE 9-11)
Moderate	40 - <60	64 - <76	46 - <64	Fairly light to somewhat hard (RPE 12-13)
Vigorous	60 - <90	76 - <96	64 - <91	Somewhat hard to very hard (RPE 14-17)
Near maximal to maximal	≥90	≥96	≥91	≥ Very hard (RPE ≥ 18)

Following review of the literature, McMorris (2016) concluded that the majority of authors determine low-intensity exercise as being ≤30 % $\dot{V}O_{2max}$, though there was a tendency for some authors to use ≤40 %, while moderate-intensity is generally 40 % or 50 % to 79 % $\dot{V}O_{2max}$ and HIE is seen as being ≥80 % $\dot{V}O_{2max}$. Most researchers do not provide any rationale for using their selected exercise intensities; more recently however, McMorris and Hale (2012) identified that the intensity ranges generally

chosen to represent low, moderate and high are very close to those identified by exercise endocrinologist Borer (2003). Borer based their classifications of exercise intensities on several endocrinological factors such as central and peripheral concentrations of catecholamines, hypothalamic-pituitary-adrenal axis hormones and cortisol; subsequently this led to the identification of low-intensity exercise as <50 % $\dot{V}O_{2max}$, moderate-intensity as 50-75 % $\dot{V}O_{2max}$ and high-intensity as ≥76 % $\dot{V}O_{2max}$. Furthermore, measures of lactate, catecholamines, cortisol and adrenocorticotropic hormone show significant increases at ≥80 % $\dot{V}O_{2max}$ (de Vries et al., 2000, Hill et al., 2008, McMorris et al., 2009). Due to this, it has recently been proposed that >80 % $\dot{V}O_{2max}$ is a safer workload to signify the lower end of ''high-intensity'' exercise (McMorris, 2016). Based on these guidelines which provide the most recent and scientifically justified reasoning for intensity categorisation, recent studies have implemented the following intensity classifications: <40 % maximal aerobic power (W_{max}) low intensity, 40 - 79 % W_{max} for moderate and ≥80 % W_{max} for HIE (McMorris and Hale, 2012, McMorris et al., 2015, Schapschröer et al., 2016). Based on the conversion formulae from Arts and Kuipers (1994), these classifications are equal to <47 % $\dot{V}O_{2max}$, 48 – 81 % $\dot{V}O_{2max}$ and ≥82 % $\dot{V}O_{2max}$ for low-, moderate- and high-intensities respectively.

The differentiation of exercise intensities is purposeful for both practical reasons and to make sense of past research. However, the biochemical responses to exercise are individually different; consequently some authors have determined moderate-intensity exercise as being greater than the LT or the catecholamine threshold (Chmura et al., 1994, Kashihara and Nakahara, 2005). Furthermore, exercise to volitional exhaustion at or above 100 % $\dot{V}O_{2max}$ as well as highly demanding intermittent exercise, determined by the amount of time working at heavy workloads, has been deemed high-intensity (Fery et al., 1997, McMorris and Graydon, 1996a, McMorris and Graydon, 1996b, Whyte et al., 2015). The influence of physical fitness and exercise intensity on cognitive performance will be considered in the following section alongside potential mechanisms of action.

1.4 Exercise-cognition interaction: Mechanisms of action

1.4.1 Physical fitness and cognition

There are many adaptations that occur due to chronic exercise training which may contribute to the beneficial effects of physical fitness on cognitive function. The most

frequently suggested mechanisms include increased brain derived neurotropic factor (BDNF) expression (Babaei et al., 2014, Zoladz et al., 2008), changes in brain morphology (Chaddock et al., 2010, Colcombe et al., 2006), increased neuronal firing (Nakata et al., 2010) and changes in plasma catecholamine levels (de Diego Acosta et al., 2001, McMorris and Hale, 2012). The adaptations from chronic cardiovascular exercise have been found to reduce a number of physical and mental disorders across the adult lifespan (Hillman et al., 2008) and alleviate cognitive decline associated with ageing (Colcombe and Kramer, 2003). Physical fitness has also been associated with greater academic achievement in schoolchildren (Castelli et al., 2007, Chomitz et al., 2009, Van Dusen et al., 2011). Together, this evidence supports the positive influence of fitness on cognitive performance. Alongside this, evidence supports an influential effect of sport training on fundamental cognitive and perceptual measures outside the sport-specific domain (Chaddock et al., 2011, Voss et al., 2009).

Brain morphology is one of the key adaptations associated with chronic exercise. Non-athletes undertaking exercise have been shown to have enhanced grey matter volume in several brain regions, including the dorsolateral prefrontal cortex (Weinstein et al., 2012), basal ganglia and hippocampus in children (Chaddock et al., 2010) and adults (Becker et al., 2016) and the hippocampus in elderly individuals (Erickson et al., 2009). Concerning athletes in particular, it is difficult to differentiate between exercise-induced effects and expertise training. In an attempt to do this, Schlaffke et al. (2014) compared martial arts athletes who are characterised by high skill but not necessarily high cardiovascular fitness, with endurance athletes and a sedentary population. Compared to the sedentary group, both athletic groups showed greater grey matter volumes in the supplementary motor area/ dorsal premotor cortex, including the pre-supplementary motor area. This region is extensively connected to prefrontal areas and plays a role in cognitive control, response selection and response inhibition (Dum and Strick, 1991, McMorris and Corbett, 2016, Yanagisawa et al., 2010). Tseng et al. (2013) has also evidenced greater grey and white matter tissue concentrations predominantly in the right parietal and occipital lobes, involved in visuospatial processing and motor control (Indovina and Macaluso, 2004), in masters athletes compared with sedentary counterparts. These findings may explain superior results seen by athletes, independent of sport type, on neurobehavioural tests of executive function and visuospatial attention when compared to non-athletic populations, as observed by Alves et al. (2013).

From a theoretical perspective, exercise-induced increases in grey and white matter would likely be caused by, amongst other growth factors, increases in brain concentrations of BDNF and BDNF messenger ribonucleic acid expression (McMorris and Corbett, 2016). BDNF is part of a family of proteins called neurotrophic factors or “growth factors”, which are directly involved in neuronal and synaptic growth. In particular, BDNF is vital for short-term cognitive performance and long-term brain morphology (e.g. plasticity) (Piepmeier and Etnier, 2015) which has led to it receiving extensive attention (Cirulli et al., 2004, Ferris et al., 2007, Huang et al., 2014). Correlational studies have frequently reported negative associations between aerobic fitness and peripheral BDNF (pBDNF) (Babaei et al., 2014, Chan et al., 2008, Currie et al., 2009, Nofuji et al., 2008), with athletes often being found to have lower circulating pBDNF levels than sedentary individuals (Babaei et al., 2014, Nofuji et al., 2008). It is currently not clear why relatively low pBDNF levels in higher-fit individuals are positively associated with better cognitive function, though a more efficient uptake mechanism of pBDNF through the blood-brain barrier (BBB) into the central nervous system (CNS) has been suggested (Hwang et al., 2017).

One of the main hypotheses proposed to be the driving force behind the positive benefits of physical fitness on cognitive function surrounds the beneficial adaptations that occur due to improvements in cardiovascular function. Known as the “cardiovascular fitness hypothesis”, this theory proposes that physical fitness is the mediator that explains the relationship between physical exercise and improved cognitive performance (Etnier et al., 1997). The premise for this is that cardiovascular training is associated with many adaptations that support more efficient function of neurotransmitters and neural circuits leading to improved cognitive performance (Dustman et al., 1984).

Though evidence demonstrating exactly how improved cardiovascular fitness is related to adaptations in the brain is limited, functional magnetic reasoning imagining studies provide overwhelming support for a regionally selective association for prefrontal cortex (PFC) function (for review see Voss 2016). It is suggested that this may be because the cardiovascular related adaptations have the greatest effect in regions with the most vulnerability during development and ageing, such as the PFC (Billinger et al., 2017, Voss, 2016). Interestingly, this supports neurobehavioural findings that suggest physical fitness has the greatest effect on tasks of executive function (Chang et al., 2014, Colcombe and Kramer, 2003). Furthermore, this may also support the mechanistic rationale proposed by Llorens et al. (2015) to explain their findings of superior cognitive performance in trained individuals. Llorens and

colleagues explain that as physical exertion requires increased activity of motor and sensory brain regions compared to rest (Dietrich, 2006) and requires the modulation of brain metabolism (Secher et al., 2008); having greater fitness levels would lower the magnitude of changes in brain metabolism and functioning, particularly during HIE. Equally, individuals with lower fitness levels would require more metabolic resource in areas of the brain not as involved in cognitive functioning, such as the motor cortex. Due to the competitive environment, the loss of resource to other areas of the brain may reduce cognitive capacities. Interestingly, findings from a neuroimaging study examining brain glucose uptake during different intensities of exercise reports a potential effect of physical training on brain metabolism (Kemppainen et al., 2005). This study found trained subjects had a more pronounced decrease in glucose uptake in the frontal lobe area compared to less-trained participants. To compensate for the increased energy needed to maintain neuronal activity, the brain metabolises lactate. Regional analysis indicated that this finding was restricted to superior and medial frontal cortex and the dorsal ACC which is associated with cognitive, motor planning, emotional processing and autonomic functions (Kemppainen et al., 2005). Whilst it is unknown what mechanism causes this adaption, it does highlight that training can elicit adaptive metabolic changes in the brain.

Though the exact mechanism behind greater fitness levels and superior cognitive functioning is not fully understood, it is believed that cognitive responses to acute exercise may be different in athletic populations. The following section will focus on the potential mechanisms underpinning the effect of acute exercise on cognitive performance.

1.4.2 Acute exercise and cognition

Early research investigating the interaction between exercise and cognition was atheoretical and appears to have been purely discovery work based on the whims of researchers (Gutin, 1966, Gutin and Di Gennaro, 1968, McAdam and Wang, 1967, Meyers et al., 1969). This changed from the early 1970s however, when exercise was viewed as a stressor that could affect bodily systems in the same way as other stressors (Davey, 1973, Levitt and Gutin, 1971, Sjöberg, 1975). Since this early work, several mechanisms have been suggested to explain the effect of exercise on cognitive function, these include: exercise-induced arousal (Audiffren et al., 2009, Davey, 1973, Lambourne and Tomporowski, 2010, Tomporowski, 2003), changes in

plasma catecholamines (Chmura et al., 1994, Cooper, 1973), regulation of neural resources (Dietrich, 2003, Dietrich, 2006), and the synthesis of BDNF (Ferris et al., 2007; Griffin et al., 2011; Winter et al. 2007). This section will focus on each mechanism, succinctly discussing their application to acute exercise and cognitive function.

Arousal "is the intensity dimension of behaviour" and has been defined as a "general state of activation" that is typically associated with increases in heart rate, respiration and sweat response (Gill et al., 2017), as well as the amount of resources available to the CNS (McMorris et al., 1999). The longest standing theory regarding the effect of acute exercise on cognitive function is that of exercise-induced arousal, which has gone on to form the basis of many subsequent models. Indeed this concept has been studied extensively since its initial proposal by Davey (1973) and has received subsequent support (Brisswalter et al., 1995, Chmura et al., 1994, Hüttermann and Memmert, 2014, Lambourne and Tomporowski, 2010, Tomporowski, 2003). Davey (1973) applied Yerkes and Dodson's (1908) inverted-U hypothesis to an exercise and cognition paradigm, seeing exercise as a stressor that caused an incremental rise in arousal as intensity increased. Their investigation provided evidence for an inverted-U effect of exercise-induced arousal on cognitive performance, which was later supported by Sjöberg (1975). Since this initial theory, the inverted-U effect has provided a foundation for many other models; a particular evolution of this came in the form of cognitive energetic-models (Kahneman, 1973, Sanders, 1983). These theories are based on individuals having a limited amount of resources and suggest that as arousal increases to moderate levels, an improvement in performance will only occur if resources are allocated. Sanders (1983) model in particular suggests that if sufficient resources are available, low arousal may act similarly to moderate arousal on cognitive performance. These models postulate however that high-intensities would cause random inherent fluctuations in neural networks, termed "neural noise", which inhibit optimal cognitive performance.

The catecholamine hypothesis initially proposed by Cooper (1973), is closely linked to theories of exercise-induced arousal but attempts to provide a more scientifically robust method using a neurophysiological explanation. Catecholamines are a group of neurotransmitters secreted by cells in the brain, with the most abundant being adrenaline, noradrenaline and dopamine. Exercise causes the release of catecholamines, these then induce increases in dopamine and noradrenaline concentrations in the brain, which subsequently cause the activation or inhibition of neurons. This is responsible for facilitating CNS arousal and it is proposed that these

neurophysiological changes could be responsible for the changes in cognitive performance seen during and after exercise, though consensus on this is still unclear (Chmura et al., 1994, Cooper, 1973, McMorris et al., 1999, Winter et al., 2007).

In a study examining the relationship between graded exercise, plasma catecholamine thresholds and choice-reaction time (CRT), Chmura et al. (1994) observed an inverted-U effect where beyond an optimal point, increases in plasma catecholamine levels resulted in a rapid deterioration of cognitive performance. In support of this, McMorris et al. (1999) reported improvements in a sport-specific decision-making test together with a rise in adrenaline levels during exercise and Grego et al. (2004) found an increase in P300 amplitude, as measured by electroencephalography (EEG), between the 72nd and 108th minute of prolonged moderate-intensity cycle ergometry which disappeared following 2-hours of exercise. As the P300 is considered to reflect a manifestation of CNS involvement with the processing of new information, the results may be indicative of an improvement in cognitive function following up to 2 hours of exercise, with further exercise leading to fatigue-induced alterations in information processing speed. Furthermore, the reduction in P300 amplitude past 2 hours' exercise was in line with significant rises in adrenaline and noradrenaline from baseline. Evidence supporting this hypothesis however is not conclusive. McMorris and colleagues (2000) found no change in speed of decision-making on a psychomotor soccer-skill test and failed to provide support for a direct effect of increased catecholamine concentrations on cognitive performance during exercise (McMorris et al., 2008). This evidence suggests there is a likely relationship between catecholamines and cognitive function during exercise, though not direct.

Similarly to cognitive-energetic models, the transient hypofrontality hypothesis (Dietrich, 2003) is based on the concept that the brain has a limited information processing capacity (Broadbent, 1958) as global cerebral blood flow, global metabolism and global oxygen uptake to the brain are constant (Ide and Secher, 2000), and thus there are no additional metabolic resources available during exercise. As each area of the brain is highly competitive, the brain must allocate resource to where it is most needed. During exercise there is a large and sustained activation of motor pathways (i.e. primary and secondary motor cortices, basal ganglia, cerebellum) as well as sensory (i.e. primary sensory cortex) and autonomic (i.e. hypothalamus) systems which must take priority for exercise to continue (Vissing et al., 1996). Because of this, there is a downregulation on resource to the PFC during exercise, causing a temporary inhibition of brain regions that are not essential to

exercise and this temporarily impairs performance on prefrontal-dependent tasks that are mostly those of higher cognitive functions.

Though there is sound theoretical evidence for hypofrontality, empirical evidence has been mixed. Some evidence concerning impairment to behavioural performance of attentional or executive tasks during exercise has been reported (Del Giorno et al., 2010, Dietrich and Sparling, 2004, Wang et al., 2013), but equally improvements in performance have been reported during prolonged (Pesce et al., 2003), moderate (Hung et al., 2013) and high-intensity (Davranche et al., 2015, Schmit et al., 2015) exercise. A recent study by Tempest et al. (2017) used both a behavioural assessment of executive function and near-infrared spectroscopy to detect changes in brain activity via oxyhaemoglobin concentrations (O_2Hb). Interestingly, 60-minutes of cycling at a physiologically challenging intensity improved RT on the Eriksen flanker task (indexing inhibitory control; Machado et al. 2007) but impaired performance on the 2-back task (reflecting WM efficiency). Moreover, no inverse pattern of oxygenation between prefrontal and motor regions was observed as exercise duration progressed. Schmit et al. (2015) and Ando et al. (2011) have also failed to find a relationship between behavioural task performance on the Eriksen flanker task and reductions in right frontal cortex oxygenation during strenuous exercise. This is particularly surprising since the right inferior frontal cortex is an important component in inhibition processes (Aron et al., 2004). These findings raise an interesting point regarding the effect of exercise on executive function. The finding that inhibitory processes are facilitated with exercise but WM processes are impaired supports the notion that, despite both being classed as executive processes, they are indeed separate and should not be generalised (Miyake et al., 2000). Furthermore, it is important to consider that different executive processes rely on different neural networks and thus downregulation of the PFC may be more prominent on particular tasks (Radel et al., 2017).

An increase in peripheral BDNF (pBDNF) levels during (Rasmussen et al., 2009) and following (Ferris et al., 2007, Griffin et al., 2011, Lee et al., 2014, Rasmussen et al., 2009, Skriver et al., 2014, Tonoli et al., 2014, Tsai et al., 2014a, Winter et al., 2007) exercise has led to the theory that this mechanism may be responsible for exercise-induced cognitive enhancement. Winter et al. (2007) assessed 27 healthy male participants on a novel language-learning task following a rested condition, moderate-intensity and high-intensity exercise. Vocabulary learning was faster and BDNF levels higher after the intense exercise condition compared to the other two conditions. Furthermore, the maintenance of pBDNF concentrations post-exercise positively

correlated with better short-term learning performance, highlighting the potential role of BDNF as a mediator of improved learning following physical exercise. Griffin et al. (2011) also reports similar findings, with intensity-dependent increases in pBDNF and improvements in memory performance on a face-name matching task, known to recruit the hippocampus but not on Stroop task performance that primarily recruits the frontal lobe. These results are not uncommon, with positive correlations often being reported when studies assess pBDNF alongside a measure of memory (Lee et al., 2014, Skriver et al., 2014, Winter et al., 2007) but not when studies assess other cognitive domains (Ferris et al., 2007, Tsai et al., 2014a). It is important to emphasise openly that many of the theoretical models commonly used in current literature to explain post-exercise changes in cognitive function were designed specifically to account for the psychological effects during exercise. Given the lack of detailed data about the time it takes for the brain to resume pre-exercise status, there is uncertainty regarding the applicability of these frameworks to cognitive function when assessed post-exercise. There are very few theoretical frameworks specifically explaining exercise-induced cognitive changes post-exercise, perhaps due to the challenges and limitations in neurophysiological assessment.

1.5. Exercise-cognition interaction: Moderating factors

1.5.1 Exercise intensity

Low-intensity exercise has most commonly been examined when used to assess the inverted-U effect of exercise intensity on cognitive function. Wang et al. (2013) found no effect of 30-minutes low-intensity cycling exercise (30 % HRR) on shifting and problem-solving executive functions in young healthy adults when compared to a seated control. These results are echoed by Kamijo et al. (2004b) who found no change in P300 amplitude following low-intensity cycling, judged as an RPE of 7-9 on the Borg 6-20 scale (Borg, 1998). In a later study, Kamijo et al. (2009) assessed inhibitory control in healthy young and older adults following 20-minutes of light exercise (30 % $\dot{V}O_{2max}$) and reported no significant changes in RT in either group, though P300 latency was significantly shorter following exercise than the baseline session. This finding led the authors to suggest stimulus evaluation processes were facilitated. Conversely, Ferris et al. (2007) assessed performance on inhibitory control using the Stroop test following 30-minutes` low-intensity exercise (20 % below ventilatory threshold; VT) and found improved performance in young physically active

students. In support of this, a meta-analysis indicated overall beneficial effects of low-intensity exercise on aspects of cognitive function immediately following exercise, though no moderating effect of any exercise intensity on cognitive function was observed when testing was conducted during exercise (Chang et al., 2012).

Moderate-intensity exercise has received the most attention regarding its effect on cognition, likely due to increased health benefits compared to low-intensity exercise (Warburton et al., 2006). In alignment with early theories of an inverted-U effect, much of the research examining moderate-intensity exercise reports facilitative effects. Kamijo et al. (2009) found an improvement in RT performance on a modified flanker task during 20 minutes of exercise at 50 % $\dot{V}O_{2max}$ in both younger and older male adults. Similarly, Pesce and Audiffren (2011) assessed younger and older adults during moderate-intensity exercise but on a much larger scale, with a total of 100 participants. During exercise at 60 % HRR, a facilitative effect on CRT speed of response was reported. Chang et al. (2011) had 20 participants exercise at a moderate-intensity (69 % HRR) on a cycle ergometer for 20 minutes and reported facilitative effects for both accuracy and response speed in the Tower of London task, indicating a facilitative effect on planning and problem solving. Furthermore, improvements with moderate-intensity exercise appear to be independent of fitness-level, as facilitative effects have been observed in both untrained (Joyce et al., 2009) and endurance-trained (Hogervorst et al., 1996) individuals. Though the authors determined this intensity to be strenuous in the latter study, as previously discussed more recent guideline places their work at the higher-end of moderate-intensity.

Indeed, there are studies that indicate negligible or even detrimental effects on cognition during and/or following moderate-intensity exercise (Del Giorno et al., 2010, Moore et al., 2012), though collectively these studies are in the minority. This is reinforced by an overall review of studies examining the effect of moderate-intensity exercise on cognitive performance, where McMorris (2016) identified that 28 of 32 studies found facilitative effects on either speed or accuracy of cognitive tasks. Additionally in a comprehensive meta-analysis of the acute effects of exercise on cognitive performance, Chang et al. (2012) found an overall positive effect for moderate-intensity exercise when cognitive tasks were administered immediately following exercise and following more than a 15 minute delay. While recreational athletes and those interested in general health benefits exercise at moderate-intensity, high-level athletes regularly train to push their own limits of performance and as such, they frequently partake in exercise intensities greater than what is considered moderate.

High-intensity exercise places greater demands on anaerobic metabolism than lower intensities. Limitations in energy supply (e.g. phosphocreatine) and intramuscular accumulation of metabolic by-products (e.g. lactate, H+, inorganic phosphate) associated with strenuous exercise have been attributed as the cause of physical fatigue (Tomlin and Wenger, 2001). Though some researchers have suggested that cognitive control is “extremely robust” and not influenced by the intensity of exercise (Davranche et al., 2015), theoretical, experimental and anecdotal literature converges towards an impairment of cognitive performances (Ando et al., 2005, Chmura et al., 1994, Chmura and Nazar, 2010, Cooper, 1973, Covassin et al., 2007, Dietrich, 2006, Dietrich and Audiffren, 2011, Wang et al., 2013). Fery et al. (1997) reported an impaired RT during exhaustive exercise in young male adults and McMorris et al. (2009) found detrimental effects of exercise at 80 % W_{max} on concomitant flanker task performance. In a larger study, Covassin et al. (2007) assessed neurocognitive function in 102 male and female recreational athletes following a maximal treadmill test to exhaustion. Post-exercise reductions in immediate recall memory and delayed recall memory, but not visual memory, motor processing speed or RT were observed. The diverse effects seen in different aspects of memory and other cognitive domains provides evidence for task-specific effects of exercise, a point that will be discussed further in section 1.5.4. In two studies, Kamijo et al. (2004a, 2004b) reported a reduction in arousal and in attentional resource allocation, as indicated by the P300 component, following HIE to volitional exhaustion. In a recent investigation, Schmit et al. (2015) assessed changes in cognitive control via the Eriksen flanker task during intense exercise (85 % W_{max}) to volitional exhaustion in 15 young healthy individuals. Most notably, Schmit and colleagues were interested in examining cognitive performance at two particular time points, at the start and end of strenuous exercise. Interestingly, facilitative effects were observed shortly following the onset of exercise, indicating that improvements in cognitive performance can occur in the first moments of intense exercise. At the point of exhaustion however, an individual’s susceptibility to incorrect responses increased and they were less capable of correcting incorrect action impulse, as measured by electromyography of the thumb muscle, despite unchanged behavioural processes.

The moderating effect of exercise intensity on cognitive performance appears well established. However, as shown in Figure 1.1, many factors influence cognitive performance and therefore exercise intensity must be considered alongside concomitant moderators to understand its interaction. The next section will explore the moderating effect of exercise mode on cognitive performance.

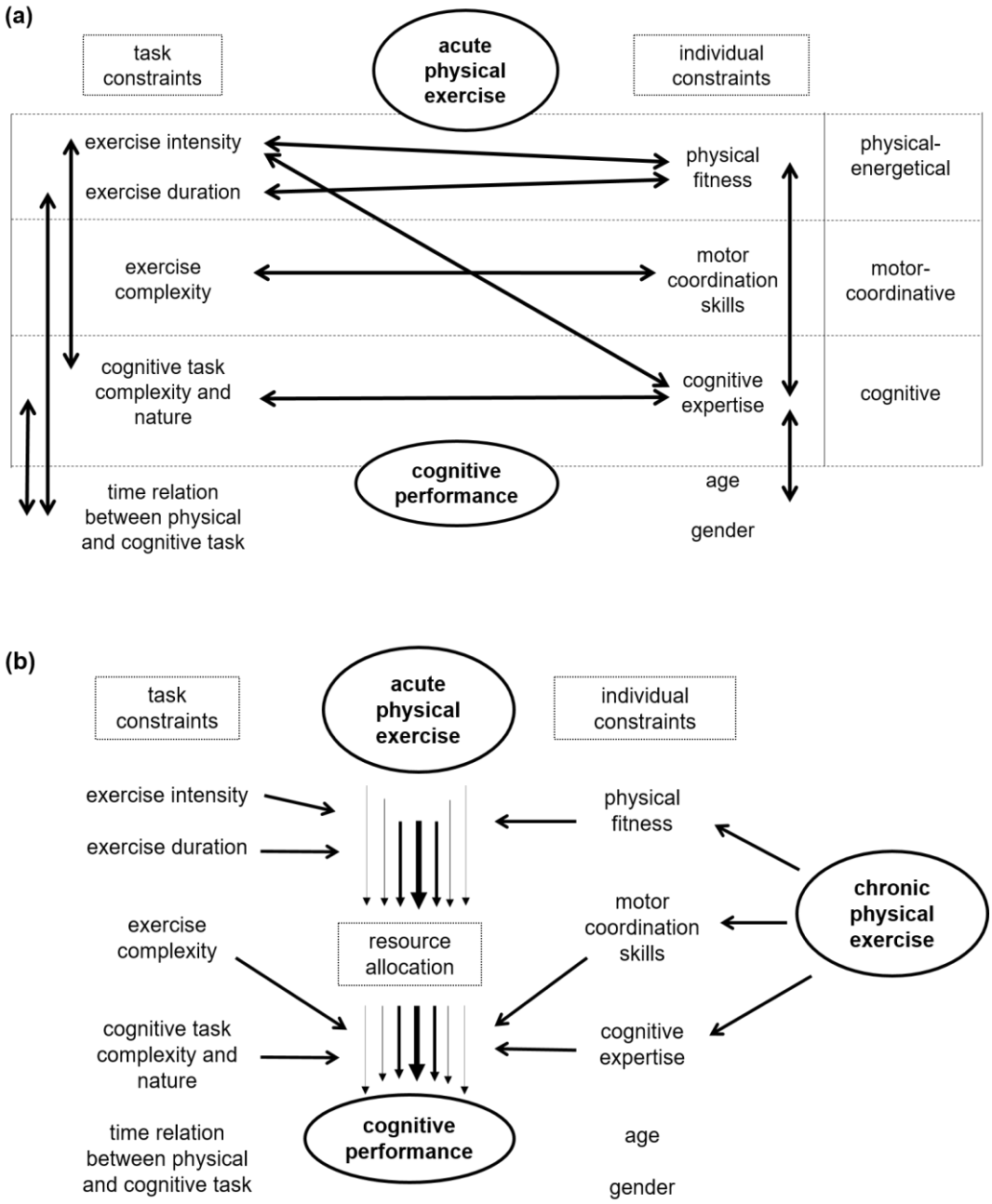

Figure 1.1 Schematic representation taken from Pesce (2009b) illustrating the effects of individual and task constraints on the acute exercise-cognition interaction: (a) arrows represent the interactions reported in the literature between individual and task constraints (horizontal arrows) and within the sub-sets of individual and task constrains (vertical arrows); (b) arrows represent the relationships hypothesised in the literature.

1.5.2 Exercise mode

A factor often overlooked despite having been demonstrated to significantly moderate the exercise-cognition interaction is exercise mode (Lambourne and Tomporowski, 2010). Ergometer cycling is the most frequent exercise modality used in the literature investigating the impact of exercise on cognitive function, followed by running (Lambourne and Tomporowski, 2010). The decision behind the selection of exercise mode is frequently unreported, perhaps due to both exercise modalities being considered to evoke similar responses. Meta-analytic assessment however has demonstrated that the cognitive response is not similar (Lambourne and Tomporowski, 2010). Interestingly, a small positive effect on cognitive performance during and following exercise was observed when cycling was used as the exercise modality. Running, however, elicited a moderate negative effect on cognitive measures during exercise. Though both exercise modes utilise large muscle groups, the physiological response is substantially different, which may explain this finding (Millet et al., 2009). Indeed, running requires greater coordination and control of body movement compared to cycling and thus it is plausible that a greater allocation of physiological and psychological resources is required. This may resultantly divert resource away from the PFC in favour of cortices regulating posture and stability, or lower the signal-to-noise ratio resulting in less efficient cognitive processing (Lambourne and Tomporowski, 2010).

The expertise of individuals may also influence cognitive processes, with familiarity being associated with the modulation of brain cortical activity (Brümmer et al., 2011). Familiar exercise has been reported to deactivate emotional brain regions, resulting in a more positive psychophysiological response at both moderate- and high-intensities. Thus, when assessed on less familiar exercise modes, cognitive performance may be affected and results may be less ecologically valid. Similar to exercise mode, the duration of exercise has a moderating effect on cognitive performance; this will be discussed in the next section.

1.5.3 Exercise duration

In a recent meta-analysis, Chang et al. (2012) found exercise durations greater than 20 minutes had positive effects on cognitive performance. Conversely, short-duration exercise lasting less than 11 minutes had no effect on cognitive performance and exercise durations between 11-20 minutes resulted in negative effects. In line with

this, it is generally considered that submaximal exercise lasting between 20–60 minutes is most beneficial for cognitive enhancement (Tomporowski, 2003) and in reducing negative psychological states such as anxiety (Petruzzello et al., 1991). When exercise duration lasts more than 60 minutes however, the appearance of fatigue symptoms may compromise cognitive functions (Brisswalter et al., 2002).

Research investigating cognition during or following prolonged exercise lasting greater than 60 minutes is limited. In one study investigating prolonged continuous exercise over one hour, Grego et al. (2005) found facilitative effects of moderate-intensity exercise (~60 % $\dot{V}O_{2max}$) up to 2 hours. During exercise from 2-3 hours and immediately post-exercise however, cognitive performance was impaired on both simple and complex cognitive tasks. It is known that prolonged periods of exercise cause dehydration which can have deleterious effects on cognitive performance (Cian et al., 2000). However, Grego and colleagues assessed the effect of prolonged exercise with and without fluid and found no difference in cognitive performance between conditions despite a significant 4.1 % loss in body mass in the no-fluid condition. From this Grego et al. (2005) speculated that the reductions in cognitive function observed may have been due to the fatigue phenomenon, causing a redistribution of neural resources to areas that are considered a greater priority, such as the motor cortices. Alternatively, since levels of catecholamines increase over time regardless of exercise intensity (Chmura et al., 1998), the results may indicate that once a certain, and perhaps individual, catecholamine threshold is reached, impairments in cognitive performance are observed. This may explain how other moderators, such as physical fitness, cause differences in cognitive responses. As the duration of HIE is limited by anaerobic metabolism, there is a shortage of research specifically investigating the effect of exercise duration and HIE. Much of this research investigates exercise to volitional exhaustion, which typically lasts 8-12 minutes.

1.5.4 Cognitive task type

As previously discussed in section 1.2, cognitive domains are derived from different cortical networks within the brain and thus in experimental research, it is important that multiple domains be assessed to gain a true understanding and representation of effects. This is particularly important since most narrative reviews (McMorris and Graydon, 2000, Tomporowski, 2003) and meta-analyses (Chang et al., 2012, Colcombe and Kramer, 2003, Etnier et al., 1997, Lambourne and Tomporowski, 2010, McMorris and Hale, 2012) have identified task type to be a moderating variable within

the exercise-cognition relationship. Though task-type categories and descriptions do vary amongst reviews, increasing evidence supports the notion that the effects of acute exercise vary by the domain of cognitive function assessed.

At the time of Etnier et al. (1997) meta-analysis and Tomporowski (2003) narrative review, the majority of the acute exercise literature focused on tasks that assessed basic information processes such as simple reaction time (SRT), CRT, visual searches and coincident anticipation. Recently however, there has been particular interest in executive functions (Chang et al., 2011, Davranche and McMorris, 2009, Dietrich and Sparling, 2004, Etnier and Chang, 2009, Hillman et al., 2003, Sibley, 2006, Sudo et al., 2017, Tempest et al., 2017, Tomporowski, 2005, Tsai et al., 2014b, Wang et al., 2013). Though domains of executive function rely on the same fronto-cingulo-parietal network (Niendam et al., 2012), a growing body of neurophysiological evidence indicates that these functions are underpinned by different neural networks which provide separate functional outcomes (Miyake et al., 2000). In studies that have assessed multiple subcomponents of executive function (Drollette et al., 2012, Moore et al., 2012, Soga et al., 2015, Tempest et al., 2017), different effects of exercise have been observed. Thus, while current evidence appears to indicate that executive control is more sensitive to acute exercise than other cognitive domains, emerging evidence suggests that generalising subcomponents of executive function may mask differential effects of exercise (Tempest et al., 2017).

Recently, Chang et al. (2012) reported a significantly larger overall positive effect of acute exercise on executive tasks than any other cognitive domain assessed and independent of when the task was administered. These results are supported by those of McMorris et al. (2011) who report moderate-to-large positive effects of exercise upon central executive tasks. It is important to consider these effects in combination with the previously discussed moderators of performance; it is however interesting that many empirical studies have demonstrated detrimental effects of acute exercise on executive processes (McMorris et al., 2009, Mekari et al., 2015, Moore et al., 2012, Smith et al., 2016a, Wang et al., 2013, Whyte et al., 2015).

1.5.5 Duration of exercise induced changes in cognitive function

Whether facilitative or detrimental effects of exercise are observed on cognitive function during and/or following exercise, it is important to establish the longevity of the observed effect to be able to make helpful recommendations. Surprisingly, there

are relatively few studies that have thoroughly examined cognitive changes over time following exercise cessation (Lambourne and Tomporowski, 2010). Though the theory of exercise-induced arousal (discussed in section 1.4.2) postulates a reduction in cognitive performance in line with the time elapsed from exercise cessation, a meta-analysis of several studies has not substantiated this (Lambourne and Tomporowski, 2010). In a recent meta-analytic review, Chang et al. (2012) found cognitive tests administered 11-20 minutes after exercise result in the biggest effects which subside following a longer (>20-minute) delay. The authors suggest that the mechanisms underlying cognitive benefits are impacted by exercise intensity and the associated physiological response (e.g. heart rate, BDNF, endorphins, serotonin, dopamine).

Brisswalter et al. (1997) assessed SRT during and immediately following exercise at different intensities and though a deterioration in cognitive performance during exercise was observed, these effects appeared to dissipate immediately post-exercise. Similar results were also reported by Collardeau et al. (2001) who assessed SRT during a 90-minute moderate-intensity run as well as immediately after, 2-minutes, and 5-minutes post-exercise. Following exercise cessation effects on cognitive function were found to diminish from 2-minutes onwards. Audiffren et al. (2009) examined two subcomponents of executive function - inhibition and updating of WM - in untrained individuals before, during and following 35 minutes moderate-intensity cycling. Effects observed during exercise were not evident upon immediate termination of exercise. Contradictory findings however have been reported by Joyce et al. (2009) in a study specifically designed to assess the time-course effect of exercise on cognitive function. Facilitative effects in response execution and inhibition (measured by a stop-signal task) were sustained for up to 52 minutes following 30-minutes of low-moderate intensity cycling (40 % W_{max}) in young untrained individuals. In a similar study design, Hung et al. (2013) assessed the planning domain of executive function via the Tower of London task prior to, immediately following, 30-minutes post- and 60-minutes post-exercise at moderate-intensity (60-70 % HRR) in young individuals. Positive effects of the exercise bout were observed immediately following exercise cessation as well as better performance following 30 and 60 minutes. These beneficial effects may have been observed at time periods in excess of 60-minutes, though as this was not assessed the full-duration of cognitive facilitation cannot be determined. Interestingly, Tsukamoto et al. (2016a) found beneficial effects of high-intensity interval exercise on executive processes (assessed via the Stroop task) up to 30-minutes post-exercise whereas moderate-intensity

exercise returned to baseline within the same timeframe. In a follow-up study examining repeated high-intensity interval exercise, similar effects were observed though post-exercise benefits following the second exercise bout only lasted up to 10-minutes before returning to baseline (Tsukamoto et al., 2016b).

1.5.6 Moderating effects of physical fitness and cognitive expertise

As discussed in section 1.4.1, increasing evidence highlights the profound effects that chronic exercise can have on brain function and cognition. Converging evidence from a number of neuroimaging and neurophysiological techniques has illustrated changes in sensory, motor, and autonomic regions of the brain (Kramer and Erickson, 2007), alongside larger regional brain volumes (Tseng et al., 2013), reinforced neural networks (Nakata et al., 2010), and increased neuroplasticity (Knaepen et al., 2010) in individuals with higher physical fitness levels. It therefore appears complimentary that facilitative effects on behavioural performance should be observed in individuals with greater fitness levels.

Indeed, Tomporowski and Ellis's (1986) review claimed physically fitter individuals could perform better on cognitive tasks than individuals who had lower physical fitness. In support of this, further narrative (Brisswalter et al., 2002, Tomporowski, 2003) and meta-analytic (Chang et al., 2012, Etnier et al., 1997, McMorris et al., 2011, McMorris and Hale, 2012) reviews have highlighted physical fitness as a key moderator of the acute exercise-cognition relationship. Longitudinal studies have demonstrated that chronic exercise leading to increased physical fitness has been shown to have positive effects on cognitive performance (Angevaren et al., 2008, Barnes et al., 2003). Given the improvements in cognitive performance and the beneficial changes cardiovascular exercise has on cerebral structure and function (Erickson et al., 2009, Voss et al., 2010), it is plausible that individuals with high-fitness levels may receive greater benefits from an acute bout of exercise than individuals with low-fitness levels. However, empirical studies exploring the moderating influence of fitness levels have yielded inconsistent results.

Themanson and Hillman (2006) found individuals with fitness levels above the 80th percentile (based upon ACSM guidelines) had greater action monitoring ability, as indicated via EEG measurements, compared to individuals with lower-fitness. This study however, failed to find differential effects of 30-minutes moderate-intensity exercise relative to fitness levels on executive processes. Similar findings have been

reported in adolescents, with physical fitness but not acute exercise modulating event-related potential indices for executive control (Stroth et al., 2009b). In an initial review, Tomporowski and Ellis (1986) concluded that strenuous exercise would have differential effects on cognitive abilities in subjects of different fitness levels. Two subsequent studies designed to substantiate this conclusion however failed to provide supporting evidence (Tomporowski et al., 1987). On examining the effect of cardiovascular fitness, Etnier et al. (1997) reported significantly larger effect sizes for cross-sectional/correlational designs (ES=0.53) and chronic designs (ES=0.33) than acute exercise intervention studies (ES=0.16) and indeed, studies assessing behavioural (Fleury et al., 1981b, Travlos and Marisi, 1995), and neurophysiological indices (Magnie et al., 2000) provide opposing evidence. Nevertheless, a considerable amount of literature provides supporting evidence for a moderating effect of fitness level on cognitive function, thus indicating a potential relationship that requires further examination.

Pesce et al. (2011) compared performance on a go/no-go task while cycling at 60 % HRR in 16 older road cyclists (60-80 years old) with 16 age-matched endurance-trained non-cyclists and 16 sedentary individuals. When compared to sedentary untrained individuals, both trained groups had faster RT during physical exercise, suggesting the chronic practice of endurance sports positively moderates the relationship between acute exercise and attentional RT. A weakness of this study however is that fitness assessment was not objectively assessed nor did the authors report the duration of the exercise bout and thus, while the trained individuals were experienced in their respective sports, the effect of their cardiovascular fitness in relation to their cognitive performance cannot be inferred. Labelle et al. (2014) assessed executive control via a modified Stroop task in higher- ($\dot{V}O_{2max}$ = 50.6 ml.kg^{-1}.min^{-1}) and lower- ($\dot{V}O_{2max}$ = 38.3 ml.kg^{-1}.min^{-1}) fit individuals during a 6.5 minute bout of exercise at either 40 %, 60 % or 80 % of their W_{max}. Deleterious effects when exercising at the highest intensity were reported but only in lower-fit individuals who had an increase in RT for the inhibition non-switch trials of the Stroop task switching condition. In a similar study, Brisswalter et al. (1997) examined the effect of fitness level on SRT while cycling at either 20, 40, 60 or 80 % W_{max}. Individuals with greater fitness levels ($\dot{V}O_{2max}$ = 64.1 ml.kg^{-1}.min^{-1} vs 42.2 ml.kg^{-1}.min^{-1}) were unaffected by the exercise bout whilst lower-fit individuals demonstrated a deterioration in RT at all intensities, with the most pronounced being at 80 % W_{max} compared to baseline. In a study examining cognitive performance post-exercise, Llorens et al. (2015) found individuals with lower fitness levels had reduced attentional control following a

maximal test to exhaustion, while individuals with higher fitness levels maintained performance. The beneficial effects of fitness and acute exercise have also been supported by a recent meta-analysis reporting significant benefits of acute exercise on cognitive performance for people with high fitness levels (Chang et al., 2012). One limitation of this meta-analysis conclusion is that the majority of the studies assessed the effects in individuals with moderate fitness, with fewer studies examining the effects in high or low fitness individuals.

Beneficial effects of greater fitness levels on electrophysiological indices following acute exercise have been observed (Tsai et al., 2014a). Two groups were formed following the assessment of $\dot{V}O_{2max}$ forming a high-fitness group ($\dot{V}O_{2max}$ = 58.0 ml.kg^{-1}.min^{-1}) and low-fitness group ($\dot{V}O_{2max}$ = 36.0 ml.kg^{-1}.min^{-1}). Following 30-minutes of moderate-intensity exercise at 60 % $\dot{V}O_{2max}$, both groups had shorter RT on a visuospatial attention task and increased central contingent negative variation (CNV). However, only individuals with higher fitness levels were found to have greater P300 amplitude and increased frontal CNV after acute exercise. The authors indicate that the CNV results may suggest that the function of "cognitive" preparation processes could be enhanced via acute exercise for higher-fit individuals while greater P300 amplitude may indicate more efficient allocation of attentional resources. The failure to find a fitness-related difference in behavioural performance supports others that have suggested aerobic fitness has the greatest effect on cognitive control processes relative to other aspects of cognition (Colcombe and Kramer, 2003, Kamijo et al., 2010).

There has been debate over potential ceiling effects of fitness on cognitive performance, or whether above average fitness levels provide greater benefits (McMorris and Corbett, 2016). This was addressed in a study by Chang et al. (2014) who investigated the role of cardiovascular fitness on Stroop test performance before and after 20-minutes of cycling at 65 % $\dot{V}O_{2max}$. Participants were placed in one of three groups based upon a tertiary split and were classified as having poor, good and super fitness for men and poor, excellent and superior fitness for women aged 20-29 according to the ACSM guidelines (see section 1.3.1): low fitness group (mean $\dot{V}O_{2max}$ = 35.25 ml.kg^{-1}.min^{-1}), moderate fitness group (mean $\dot{V}O_{2max}$ = 45.52 ml.kg^{-1}.min^{-1}) and high fitness (mean $\dot{V}O_{2max}$ = 56.21 ml.kg^{-1}.min^{-1}). Improvement in performance was found in all three fitness groups indicating that fitness level did not affect the positive relationship between acute moderate exercise and cognition. Interestingly however, in the incongruent condition, the moderate fitness group displayed the shortest RT and the longest RT was observed in the high-fitness group. The authors

suggest this indicates that there are no additional benefits of extremely high fitness, as judged relative to ACSM norms, and that there may be an inverted-U dose-response relationship between fitness and cognition. One difficulty with this conclusion is that it does not explain why moderate, but not high-fitness individuals would benefit from exercise-induced cognitive benefits (Erickson et al., 2009, Voss et al., 2010). A potential explanation for this may be derived from a study by Rimmele et al. (2009), who investigated the effect of physical activity level on adrenal and cardiovascular reactivity to psychosocial stress. Within this study it was found that in a non-sporting setting, trained individuals had a reduced reactivity of the autonomic nervous system to psychosocial stress than untrained counterparts. Furthermore, in response to a stress test, elite sportsmen (compared to amateur sportsmen and untrained men) had the lowest cortisol, heart rate and psychological responses. Based upon this it could be suggested that greater exposure to high-pressure situations and/or exercise-induced physiological stress reduces the stress effect as individuals become more accustomed to that environment. Consequently, the results of Chang et al. (2014) may be reflecting lower physiological arousal in higher-fit participants, which consequently had a negative effect on cognitive performance.

Evidence remains equivocal regarding the effect of fitness on cognitive performance during and/or following acute exercise. The inconsistent findings may be because there is currently no well-established classification as to what ‘low’, ‘moderate’ or ‘high’ fitness is (see section 1.3.2). Furthermore, studies that do not report objective values of fitness but report the trained status make it difficult to compare studies. Presently, there are few studies in healthy adult populations examining the effect of fitness levels within an acute-exercise paradigm and thus current evidence regarding the effect of physical fitness on acute-exercise is unclear.

1.5.6.1 Athletes and cognitive expertise

Some studies that have examined the effect of cardiovascular fitness on cognitive performance have used athletic populations to represent highly trained individuals (Brisswalter et al., 1997). It has been proposed however that athletes may have superior cognitive abilities on fundamental laboratory cognitive tasks than non-athletes (Voss et al., 2009); in line with this, the use of a mixed athletic and non-athletic but trained population would potentially confound results.

Most athletes participate in life-long training, practice throughout their whole career and often start very early in their childhood. Alongside the development of physical

fitness, athletes also develop cognitive expertise as it derives from the practice of sports characterised by high demands on cognitive flexibility (Pesce, 2009b). The '*cognitive component skills'* approach focuses on whether sport expertise can transcend sport to influence fundamental cognitive and perceptual measures outside of the sporting domain (Nougier et al., 1991).

Superior performance in athletes compared to non-athletic participants has been observed on classic laboratory tests of cognitive function in the absence of any exercise or sporting context (Alves et al., 2013, Chaddock et al., 2011, Faubert, 2013, Nougier et al., 1989, Pesce et al., 2011, Pontifex et al., 2009b). Chaddock et al. (2011) examined 18 mixed-sports college athletes and 18 non-athlete college students on two general cognitive tasks, namely a psychomotor speed task and a street crossing paradigm. Results indicated athletes to be superior on both tasks, with higher street crossing success rates and faster processing speed, suggesting that cognitive skills developed in sport might transfer to performance in everyday fast-paced multitasking abilities. In support of this, Alves et al. (2013) found professional volleyball players have superior performance speed on general tasks of executive control and visuospatial attentional processing compared to inactive controls. Professional athletes have also been found to demonstrate a dramatically better ability to learn how to process complex dynamic visual scenes than high-level amateur athletes, who in turn are much better than non-athletic university students (Faubert, 2013). Moreover, general tests of executive function have been shown to predict the success of ball sports players, with better scores on general tests of executive function being significantly correlated to the number of goals and assists (Vestberg et al., 2012).

To gain a greater insight into the overall effect of studies, Voss et al. (2009) performed a meta-analysis examining the relationship between sports training and core cognitive processes. From this, a small-to-medium effect was reported indicating that athletes outperform non-athletes on general laboratory measures of cognition. In particular, athletes performed better on measures of processing speed and attentional paradigms and the largest effects were seen from athletes involved in interceptive sports (e.g. hand-body coordination sports such as tennis, fencing and boxing).

The research presented so far suggests athletes possess better fundamental cognitive processes at rest. Further studies have investigated whether this is also reflected during and/or following exercise. Guizani et al. (2006a) compared the SRT and CRT of professional fencers to a sedentary control group at rest and while exercising on a cycle ergometer at 40 %, 60 % and 80 % W_{max}. The fencers

demonstrated significantly faster CRT during exercise at all intensities in addition to a main effect for SRT indicating fencers to be faster overall. It can be argued that the results of this study are likely due to the type of expertise needed by fencers rather than fitness levels. This is supported by observation of the mean $\dot{V}O_{2max}$ of the fencers, 50.7 $ml.kg^{-1}.min^{-1}$, which for their average age of 19 years would be classified as a 'good' fitness level according to the ACSM guidelines (Pescatello, 2014) and is only slightly above that regarded the norm for young males (~47 $ml.kg^{-1}.min^{-1}$) as indicated by Shvartz and Reibold (1990). As fitness levels between groups were not similar in this study, it does not provide insight into whether the training associated with athletic status gives a greater advantage over trained individuals of a similar fitness. To investigate this, Delignières et al. (1994) compared 20 expert fencers (mean $\dot{V}O_{2max}$ = 50.1 $ml.kg^{-1}.min^{-1}$) with 20 individuals who had similar fitness levels (mean $\dot{V}O_{2max}$ = 49.6 $ml.kg^{-1}.min^{-1}$) but had no expertise in decisional sports. Participants performed two CRT tasks while cycling at either 20 % 40 %, 60 % or 80 % of their $\dot{W}_{max}$. Cognitively expert athletes showed better performance speed than their non-expert counterparts, with progressive enhancements occurring as physical exertion increased. Conversely, a negative trend was observed in non-expert athletes. Similar findings have been reported by Hüttermann and Memmert (2014) who found athletes performed better at higher exercise intensities than non-athletes on an attentional task, leading authors to suggest that an inverted-U function does not appear in expert athletes but does appear in non-athletes.

Studies examining athletic populations are very limited and of the few, many are conducted without the inclusion of a control group or without comparison to trained/experienced novice athletes (Chmura et al., 1998, Davranche and Audiffren, 2004b, Davranche et al., 2006a, McMorris et al., 1999). Behavioural performance appears to be superior in athletes both at rest and during exercise, particularly at strenuous intensities and therefore the inclusion of an athletic population is thought to moderate the acute exercise-cognition relationship. It is difficult to evaluate the effect of cognitive expertise against non-athletic but highly fit individuals as there are currently few studies with adequate control examining this effect. Due to this, it is currently not possible to evaluate whether athletes have an advantage over physically active non-athletes. It can be concluded however that both physical fitness level (Chang et al., 2012) and cognitive expertise (Pesce, 2009b, Voss et al., 2009) moderate the acute exercise-cognition relationship.

There are discrepancies in the literature as to what an 'athlete' is, with some studies using professional athletes while others use collegiate athletes. As this could

influence results, guidelines have been suggested that enable both the classification of athlete and their trained status to be reported, which may help understand potential differences in results observed (De Pauw et al., 2013, Swann et al., 2015).

The first section of this literature review focussed on the effects of exercise on cognitive function and why it is important for sporting performance. The totality of evidence suggests exercise to have positive effects during and following moderate intensities on many cognitive domains. There is more uncertainty surrounding strenuous exercise intensities however and it is suggested that this is due to the influence of key moderators within the exercise-cognition relationship, such as fitness level and exercise duration. An emerging area gaining increasing support is the cognitive domain-specific effects of exercise, with their being a large body of evidence showing greater effects on higher-order cognitive functions as compared to simple processes thus highlighting the importance of assessing multiple cognitive domains. In addition to cognitive function, mood responses can be differentially influenced by exercise intensities, have been found to predict athletic performance and contribute to sporting success (Beedie et al., 2000). To gain a deeper understanding behind the effects of strenuous exercise on cognitive performance it is important to investigate contributing constructs and thus, the next sections on this review will focus on the effect of exercise on different mood states.

1.6 Exercise and Mood

Exercise is commonly reported to improve mood and enhance psychological well-being (Penedo and Dahn, 2005, Reed and Ones, 2006) as well as reducing stress, anxiety and depression (Petruzzello et al., 1991). Moods are typically defined as coherent affective states which last for minutes or hours and are different to emotions, which typically only last seconds (Mitchell and Phillips, 2007). Many reviews (Berger and Motl, 2000, Petruzzello et al., 1991, Reed and Ones, 2006, Yeung, 1996) and intervention studies (Anderson and Brice, 2011, Bartholomew and Miller, 2002, Choi et al., 1993, Head et al., 1996, Maraki et al., 2005, Maroulakis and Zervas, 1993, McGowan et al., 1991) have shown acute bouts of exercise, particularly cardiovascular exercise, can improve mood. As with cognitive function however, moderating factors influence the effect.

1.6.1 Exercise intensity

It is generally considered that moderate-intensity exercise elicits the most favourable effects for mood benefits (Zervas et al., 1993), particularly when there is an absence of interpersonal competition (Berger and Motl, 2000). Many studies have found positive effects of moderate-intensity exercise; for example, Head et al. (1996) found reductions in total mood disturbance following 1-hour of treadmill walking at 50 % $\dot{V}O_{2max}$ and following a 30-minute bout of moderate-intensity exercise at 60 % $\dot{V}O_{2max}$. In 24 healthy males, Cox et al. (2001) observed an increase in positive mood state and a decrease in negative mood state following 30-minutes of exercise at both 50 % and 75 % predicted $\dot{V}O_{2max}$. Neither of these studies, however, used a resting control group for comparison. A study that did was that of Steptoe and colleagues (1993) who investigated the relationship between exercise intensity and mood. Competitive sportsmen (n=36) and inactive men (n=36) participated in a 20-minute cycling exercise bout at either high-intensity (70 % $\dot{V}O_{2max}$), moderate-intensity (50 % $\dot{V}O_{2max}$), or light intensity (control). Following exercise, both groups exhibited increases in mental vigour and exhilaration compared to the control, with the same effects observed following exercise at both moderate and high-intensities. As previously discussed in section 1.3.2 however, recent suggestions place 70 % $\dot{V}O_{2max}$ as moderate-intensity exercise, with intensities over 80 % $\dot{V}O_{2max}$ being representative of HIE (McMorris, 2016). If we are to go by the more recent exercise-intensity guidelines, it could be argued that the failure to observe a difference in mood between the two exercise interventions was due to both being at a moderate-intensity. Nevertheless, it is interesting to observe that reductions in tension-anxiety across a maximal test were only observed in sportsmen, with inactive men reporting no change. This result has been echoed in a more recent study by Hoffman and Hoffman (2008), where improvements in vigour and reductions in fatigue were only reported among regular exercisers but not in non-exercisers. Furthermore, though total mood disturbance (TMD) improved in both groups following a 20-minute moderate–intensity exercise bout, approximately twice the effect was observed in regular exercisers compared to non-exercisers. This raises an interesting question regarding the influence of physical fitness on mood, which will be discussed further throughout section 1.6.

While it appears moderate-intensities generally facilitate mood, high-intensities have been associated with detrimental effects (Berger and Motl, 2000, Hall et al., 2002, Steptoe and Bolton, 1988, Steptoe and Cox, 1988). This may be founded on the

assumption that exercise at moderate-intensities are more enjoyable and less aversive than activities typically performed at higher intensities (Ekkekakis et al., 2000). Two studies found low-intensity exercise (25 W) to produce modest improvements in mood, as assessed via the profile of mood states (POMS) (McNair, 1971), while HIE (100 W) increased negative mood states (Steptoe and Bolton, 1988, Steptoe and Cox, 1988). The use of an absolute measure of intensity in these studies may mean that for some individuals 100 W is representative of a high-intensity, whilst for others it is not. However, other studies have shown similar findings using relative measures. For instance, increases in depression, confusion and tension were shown in competitive swimmers that exercised at or near maximal physical capability (Berger et al. (1997). Similarly, Blanchard et al. (2001) found increases in psychological distress following exercise at high (80 % age-predicated HRR) but not moderate (50 % age-predicted HRR) intensities in untrained individuals. In agreement with this, Oweis and Spinks (2001) observed higher negative affect following 10-minutes of exercise at 75 % $\dot{V}O_{2max}$ in untrained older individuals (55-65yrs). On the other hand, some reports have observed beneficial effects of HIE on anxiety reduction (Farrell et al., 1987) and self-esteem (Pronk et al., 1995).

The limited amount of research, particularly current research, and differences in methodology used to assess the impact of HIE on mood make it difficult to draw firm conclusions. One problem lies in the use of various physiological parameters to identify intensity including power, percentage HR_{max}, percentage HRR and percentage $\dot{V}O_{2max}$ (Yeung, 1996). To try to provide clarity, Berger and Motl (2000) suggest, overall, that optimal benefits occur following moderate-intensity exercise but not following low- or high-intensity exercise. These suggestions point towards the notion of either a critical intensity such as a threshold, or inverted-U relationship between exercise intensity and mood (Reed and Ones, 2006).

A different perspective considers individual perceptions, proposing the optimal exercise-induced mood benefits may be subject to large individual differences (Berger et al., 2016, Brümmer et al., 2011, Motl et al., 2000, Raedeke, 2007, Schneider et al., 2009). Assessing mood using the POMS, Zervas et al. (1993) compared mood responses following exercise at 4 different intensities: low, moderate, high and self-selected. Interestingly, the group that exercised for 30-minutes at a self-selected pace reported the greatest number of improvements across all of the POMS subscales. Indeed, not all individuals experience the same mood benefits with exercise (Raedeke, 2007) and thus, the results reported by Zervas et al. (1993) may be indicative of different levels of enjoyment which is known to have an

important role in the exercise-mood relationship (Berger, 1996, Wankel, 1993). The enjoyment individuals yield from different workloads may therefore be reflective of “flow”, described as a pleasurable state of consciousness that can only be achieved when an individual’s competencies are realistically matched against the challenges of the task (Csikszentmihalyi, 2014, Yeung, 1996). This would imply that though some individuals find the discomfort of HIE distressing, others may find it enjoyable and like the feeling of fatigue. This is in accordance with the “exercise preference hypothesis” which is built on the assumption that the relaxation effects of exercise are linked to an individual’s physical activity history and exercise preferences, where the ‘preferred’ mode and intensity of exercise is what an individual is most familiar with (Brümmer et al., 2011, Schneider et al., 2009). Indeed, support for this hypothesis has been demonstrated by Brümmer et al. (2011) who observed reductions in brain cortical activity in emotional brain regions when individuals engaged in familiar exercise. The role of exercise modality is considered further in the following section.

1.6.2 Exercise mode

Similar to exercise intensity, it is suggested that the exercise mode optimal for enhancing mood is one that an individual enjoys (Basso and Suzuki, 2017, Berger and Motl, 2000, Plante et al., 2007). Higher negative affect has been reported when individuals are told what type of exercise they must do compared to when individuals are given a choice of exercise mode (Daley and Maynard, 2003); thereby suggesting that preference may moderate the exercise-mood relationship. In a relatively large study involving 75 aerobic dance participants and 42 controls, McInman and Berger (1993) found significant positive changes in all POMS subscales except for fatigue in dance participants following 45 minutes of an aerobic dance class. Similarly, Steinberg et al. (1997) also found improvements in positive mood following two kinds of aerobic exercise (aerobic workout and aerobic dance) lasting only 25 minutes compared to a ‘neutral’ control group that watched a video. Lane et al. (2003) also assessed dance but from a more competitive standpoint. Upon assessing the impact of two different styles of dance in trained dancers, only one style of dance was found to increase vigour from baseline, indicative of enhanced mood. This suggests that the impact of dance on mood may be specific to its style, which again may be related to one’s enjoyment and/or preferred style.

Aside from dance, enhanced mood has been reported following a range of different types of activity. For example, increases in positive affect and decreases in negative affect were shown following an aerobics class in women (Bartholomew and Miller, 2002, Choi et al., 1993, Maraki et al., 2005) while Berger and Owen (1992) found both yoga (n=22) and swimming (n=37) induced reductions in anger, confusion, tension and depression compared to a control group (n=28). The improvements observed following yoga are supported by others with reports of improvements in mood and anxiety in healthy young adults (Streeter et al., 2010) and reductions in self-reported anxiety and depression in mildly depressed young adults (Woolery et al., 2004). Collectively these results indicate that exercise does not need to be aerobic to be associated with mood enhancement. In support of this, McGowan et al. (1991) found reductions in total mood disturbance, tension, depression, anger and confusion following 75-minutes of both weightlifting and running. Interestingly, they did not see similar effects in a third group who participated in a 75-minute karate class. Though the authors suggest this may have been due to karate being of lower intensity, this is difficult to determine as intensity was not measured. Moreover, this explanation seems unlikely, as positive effects have been reported following yoga, which is arguably less intense than karate. Alternatively, it could be suggested that as karate is a contact sport that involves duelling with an opponent, it may invoke very different effects on mood than less confrontational sports such as running or cycling. Furthermore, the effect of one's own performance against that of an external opponent may also affect mood. This highlights a difficulty in team sports, where elements outside of the control of the athlete (e.g. teammates moods, score, previous experience) may influence mood (Clingman and Hilliard, 1994).

In addition to enjoyment (Basso and Suzuki, 2017, Berger and Motl, 2000, Plante et al., 2007), familiarity with the exercise mode is also important when considering the effects on mood. Individuals who are familiar with a particular mode of exercise are most likely to report positive mood effects following that mode of exercise. The most constant effect of exercise on mood is found when regular exercisers undertake exercise that is familiar to them in terms of both mode and intensity (Salmon, 2001).

1.6.3 Exercise duration

Literature examining the interaction between exercise duration on mood is limited, with studies commonly exploring mood as a secondary outcome. If duration is viewed

from a chronic perspective, studies exploring the effect of intensified training (IT) on mood are more prevalent and have yielded consistent responses. Common in many sports, IT is typically carried out over a few weeks and involves training sessions of increased volume and intensity with limited recovery (Halson et al., 2002). Following 7 days of intense training, Piacentini et al. (2016) observed a 32 % rise in TMD as measured by the POMS, with the magnitude of increase being intensity dependent. Others have similarly found negative effects of IT on mood. For example Halson et al. (2002) observed a 29 % increase in TMD on the POMS following 14 days of IT in cyclists, Killer et al. (2017) observed a significant increase in TMD with time over 9 days of IT and Berger et al. (1999) observed an 8 % average increase in TMD in elite cyclists over three-weeks of IT.

When examiming literature regarding acute exercise duration and mood, meta-analyses suggest at least 21-minutes is necessary to achieve increases in positive affect (Berger and Motl, 2000) and reductions in anxiety (Petruzzello et al., 1991). However, beneficial effects have been reported following 10-minutes of exercise in young healthy regular exercisers (Anderson and Brice, 2011, Hansen et al., 2001). Anderson and Brice (2011) assessed mood on a modified POMS questionnaire before and after 10-minutes of jogging in 20 young healthy volunteers. Compared to a control group, jogging resulted in favourable effects on mood. In a study specifically looking at the effect of exercise duration and mood state, Hansen et al. (2001) investigated the effect of 10-, 20- and 30-minutes cycle ergometry at 60 % estimated $\dot{V}O_{2max}$ on mood compared to 21 healthy female rested controls. Using the POMS to assess mood state, beneficial effects were found following 10-minutes of cycling, with improvements in vigour and reductions in levels of confusion, fatigue and total mood disturbance. An additional 10-minutes of exercise provided a progressive improvement to confusion but no additional benefits were found following 30-minutes of exercise.

Though there appears a general consensus that beneficial effects on mood can be observed following only 10-minutes of light or moderate exercise, literature examining the effect of exercise duration and prolonged/high-intensity exercise is scarce. This may be because this intensity of exercise is often explored using tests to volitional exhaustion and thus duration is not considered. This presents a large gap in the literature, specifically when examining trained populations that often engage in fatiguing exercise. As with cognitive function, there is an influential effect of physical fitness on mood, with regular exercisers experiencing different mood benefits than non-exercisers. This will be explored in the next section.

1.6.4 Physical fitness and mood

It seems logical to suggest that people who partake in regular exercise do it because they enjoy it, or because they are conscious of the associated health-related benefits. In line with this, there is strong evidence supporting the superior mood effects trained individuals gain following exercise compared to sedentary individuals, with this being particularly pertinent for HIE. Steptoe et al. (1993) found reductions in tension-anxiety across a maximal test only in sportsmen, with inactive participants reporting no such change. Similarly, Hoffman and Hoffman (2008) found improvements in vigour and reductions in fatigue among regular exercisers but not non-exercisers following 20-minutes of moderate-intensity exercise. Blanchard et al. (2001) assessed feeling state responses in 12 fit ($\dot{V}O_{2max}$ = 53.79 $ml.kg^{-1}.min^{-1}$) and 12 unfit females ($\dot{V}O_{2max}$ = 32.99 $ml.kg^{-1}.min^{-1}$) following 30-minutes of cycling at 50 % and 80 % age-predicted HRR. Following the 50 % intensity condition, similar changes in psychological distress were observed between groups. However, following exercise at a greater intensity the unfit group experienced a significant increase in psychological distress, where the fit group experienced a relatively large, but non-significant decrease. The authors align these findings with that of 'opponent process theory' (Solomon and Corbit, 1974). This theory suggests that the initial feeling state reaction to strenuous exercise is driven by the "a-process" which causes discomfort. The a-process however, always arouses an opponent "b-process" which is characterised by the opposite affective quality and attempts to return to homeostasis. The interaction of these processes over time controls the intensity and quality of the affective state; the more exposure one gains to the exercise stimulus, the stronger the b-process becomes. Following this theory, it can be argued that unfit individuals find strenuous exercise more aversive than fit individuals, resulting in higher psychological distress post-exercise. Parfitt et al. (1994) found highly active subjects who exercised more than 3 times per week were significantly more positive during exercise at higher intensities (90 % $\dot{V}O_{2max}$) compared to less active individuals who trained less than twice per week. Further support comes from studies that have observed greater mood effects in fitter and more active individuals following both moderate (Boutcher and Landers, 1988) and higher (Boutcher et al., 1997) exercise intensities.

Though some reports oppose the positive interaction between mood and fitness (Choi et al., 1993, Felts and Vaccaro, 1988, Roth, 1989, Steptoe and Cox, 1988), evidence appears to be strong regarding the moderating effect. Importantly however, this appears most apparent at high exercise intensities, with light and moderate exercise

being less conclusive (Ekkekakis and Petruzzello, 1999). It is reasonable to hypothesise that individuals more accustomed to high-exercise intensities will feel more comfortable in dealing with the physiological effects than those who are not used to them.

A weakness in much of the evidence is in the failing to objectively quantify fitness, with studies often just reporting the amount of exercise participants do and classifying individuals over a certain threshold as 'fit'. This is important when the findings of Thirlaway and Benton (1992) are considered. Findings from a correlational study led the authors to suggest cardiovascular fitness and participation in exercise, though one is causative of the other, have different effects on mood and should be considered separately. Furthermore, the authors suggest that it is participation in exercise that enhances mood and thus emphasis needs to be on performing physical activity rather than improving fitness. As discussed in section 1.6.1, mood benefits from exercise should be considered on an individual basis with preferences towards certain intensities and modes of exercise influencing the effect. To avoid confounding effects of fitness level, Ekkekakis and Petruzzello (1999) recommend controlling for physical fitness particularly in studies that include high exercise intensities and/or long durations.

Evidence highlighting the importance of considering the exercise-mood relationship on an individual level may be related to the mechanisms causing the positive and/or negative effects. This will be explored in the next section.

1.6.5 Mechanisms of exercise-induced mood

Numerous physiological mechanisms have been suggested to account for the effects of exercise on mood. Exercise induces several physiological and neurochemical changes in the body which could contribute to altered mood states, these include; elevated endorphin levels (Boecker et al., 2008), alterations in central neural activity (Hall et al., 2007) and the secretion of hormones and neurotransmitters (Heijnen et al., 2016).

A popular theory that has received much interest in the literature is the endorphin hypothesis which suggests positive mood following exercise is attributed to increased endorphins in the CNS (Boecker et al., 2008, Thorén et al., 1990). Whilst it has been shown that plasma levels of endorphins are elevated following exercise of sufficient intensity and duration (Goldfarb and Jamurtas, 1997), the correlation between

peripheral and central levels of endorphins has been debated. This is due to it being unlikely that endorphin molecules would be able to pass the BBB as it is relatively impermeable to peptides and other large molecules circulating the blood stream (Berger and Motl, 2000). However, convincing evidence for the endorphin hypothesis has been provided by Boecker et al. (2008) who used positron emission tomography to provide the first human evidence of increased central endorphin levels following exercise. In this study, 10-trained athletes were scanned at rest and following 2-hours of moderate-intensity running. Following exercise, the level of euphoria (assessed via subjective ratings) was significantly elevated and inversely correlated with non-selective radioligand binding in frontolimbic brain areas, suggesting an increased uptake of endogenous endorphins.

To try to understand the different modulation in affect following moderate and high-intensity exercise, a recent study by Saanijoki et al. (2018) specifically investigated μ-opioid receptors (MOR), as these are responsible for mediating positive reward and euphoria (Chartoff and Connery, 2014). Results demonstrated that decreased radioligand receptor binding was only found following high-intensity interval training and this was associated with an increase in negative affect. Moderate-intensity activity however, did not affect MOR availability, though it did elicit positive mood and euphoria. This may suggest that specific opioid receptor activity modulates positive emotionality after moderate-intensity exercise and negative emotionality or pain after HIE (Saanijoki et al., 2018). The authors also suggest that mood is likely to be modulated by other neural factors and neurotransmitter systems, such as the endocannabinoid system (Fuss et al., 2015, Markoff et al., 1982, Sparling et al., 2003).

It has been demonstrated in mice that blocking endocannabinoids receptors, but not endorphin receptors, diminishes the anxiolytic and analgesic effects of running (Fuss et al., 2015), causing researchers to turn their attention to endocannabinoids (Sparling et al., 2003). Anandamide, a cannabinoid neurotransmitter linked to emotional and cognitive processes, freely crosses the BBB and has been reported to increase peripherally following exercise (Sparling et al., 2003). This mechanism may therefore play a significant role in the effects of exercise on mood (Dietrich and McDaniel, 2004, Brellenthin et al., 2017).

It is suggested that endorphins may interact with neurotransmitters, such as dopamine, to improve mood (Dishman and O'Connor, 2009). In line with this is the monoamine hypothesis, which states that exercise leads to an increase in the

availability of brain neurotransmitters (e.g. serotonin, dopamine, and noradrenaline) (Craft and Perna, 2004). These neurotransmitters increase in both plasma and urine following exercise, but whether exercise leads to an increase in neurotransmitters centrally is currently unknown (Craft and Perna, 2004). These theories also align well with the neuropsychological theory of positive affect (Ashby and Isen, 1999) that suggests positive mood is associated with, but not necessarily caused by, increased levels of dopamine in the brain, particularly in the PFC and anterior cingulate. Indeed, a complex set of different signalling pathways, including those activated by hormones, neurotransmitters, growth factors, and neuromodulators, are stimulated with a single bout of exercise (Basso and Suzuki, 2017), and thus it is unlikely any one mechanism is responsible.

In addition to physiological mechanisms, several psychological mechanisms have been proposed to explain the effect of exercise on mood. A popular psychological mechanism is the distraction hypothesis (Craft and Perna, 2004, Raglin and Morgan, 1985) which suggests that exercise serves as a distraction from worrisome thoughts and daily stressors. Some studies have indicated that exercise is no more effective than an equivalent period of relaxation in reducing anxiety and tension (Berger and Friedman, 1988, Felts and Vaccaro, 1988). However, as well as alleviating negative mood symptoms, exercise has been demonstrated to promote positive mood symptoms. Therefore, exercise may only be as effective as relaxation for the alleviation of negative mood states, but may be superior for the enhancement of positive mood states (Saklofske et al., 1992). From a similar perspective, Dietrich and Audiffren (2011) apply their reticular-activating hypofrontality model of acute exercise by suggesting worrying or stressful thoughts are not able to reach consciousness as the brains finite metabolic resources are diverted away from the PFC and towards higher priority areas such as the motor cortices. Though many theories have been postulated, it is highly likely that a combination of physiological, psychological, environmental and sociological factors influence the interaction between exercise and mood.

1.7 Summary of current literature

Research investigating the effect of exercise on cognition and mood has increased exponentially over the past 50 years, though the state of current research illustrates this area is still very much in its infancy. The identification of moderating factors within both the exercise-cognition and exercise-mood relationships highlights the limitations

in transferring results from studies done in sedentary populations and in studies using low or moderate-intensity exercise paradigms. Moreover, it appears that literature emphasising the cognitive domain specific effects of exercise is only recently emerging, thus calling for researchers to investigate multiple cognitive domains to provide insight on the effect of different exercise types and durations on specific cognitive domains.

The evidence evaluated in the literature review highlights the need for further research investigating strenuous exercise in healthy sporting individuals. The physiological and neurophysiological adaptations that occur with chronic training support cognitive development and thus research investigating the effect of exercise in sedentary or untrained populations cannot be transferred nor is it likely to simulate the exercise type or intensity trained sporting performers undertake.

The literature review suggests, though not conclusive, that high exercise intensities have detrimental effects on cognitive performance, specifically higher-order processes, and mood. The effect on individuals familiar with strenuous exercise and of greater fitness levels however has not been thoroughly investigated. Furthermore, an important aspect highlighted by this review is the lack of research using sport-specific exercise protocols within their research designs. In modern day sport athletes must compete in congested tournament fixtures, in competitions of prolonged durations and commit to weeks of intensified training prior to enduring competitions. To understand the stress of these paradigms on cognitive function and mood, research needs to replicate them in study designs whilst tightly controlling for moderators and confounders.

1.8 Scope of the thesis and aims

Accordingly, the primary purpose of this thesis is to examine various strenuous, HIE paradigms on cognitive performance and mood in trained and athletic populations. Chapter 2 provides a comprehensive systematic review on the current literature surrounding cognitive performance in trained populations during and following acute HIE. It then outlines the consensus to date alongside the moderating factors that influence the relationship between exercise and cognitive function. In addition to systematically reviewing current literature, the aim of this chapter was to gain insight into current understanding and identify gaps in the literature for further investigation. The subsequent three chapters' present experimental studies designed to investigate

the effect of different paradigms of exercise on cognitive performance in trained individuals of various disciplines. Chapter 3 examines cognitive processes in trained endurance cyclists following prolonged, strenuous intermittent exercise. Chapter 4 investigates the effects of congested tournament scenarios by examining the impact of repeated intermittent HIE sessions, over two-consecutive days, on cognitive performance, mood and ratings of physical and mental energy and fatigue in trained intermittent sports players. Chapter 5 presents cognitive, mood, physical performance and perceived sleep data throughout a two-week intensified cycling training period and two-week taper period in trained cyclists. Chapter 6 discusses the results of the aforementioned studies and provides an overview of the main conclusions, practical implications and future research interests.

Overall, this course of research intends to address four specific aims throughout the thesis:

1. Identify and evaluate current understanding concerning the effects of strenuous exercise on cognitive function in trained populations.

2. Examine the effect of prolonged, strenuous exercise on cognitive function mood, energy and fatigue states in trained sporting individuals.

3. Investigate the effect of multiple strenuous exercise bouts on cognitive function mood, energy and fatigue states in trained sporting individuals.

4. Characterise the effect of an intensified training intervention on cognitive function, physical performance, mood, energy, recovery and fatigue states in trained sporting individuals.

Chapter 2: The effect of acute high-intensity exercise on cognitive function in trained individuals: A systematic review

2.1 Introduction

The health benefits provided through participation in regular exercise are well established, with an abundance of evidence demonstrating increases in physical well-being and improvements to many metabolic parameters (American College of Sports Medicine, 2013, Penedo and Dahn, 2005). Additional benefits are provided for those engaged in exercise for the purpose of training, where exercise is undertaken at higher intensities and/or greater frequencies/durations (Pollock et al., 1998). A growing body of research has demonstrated that these benefits are not just limited to physical health but extend to improvements in brain function and cognition (Hillman et al., 2008). Moreover, several intervention studies have found superior cognitive performance in trained subjects compared to untrained (Colcombe and Kramer, 2003, Tomporowski and Ellis, 1986), signifying a positive influence of physical fitness on cognition. Converging evidence from a number of neuroimaging and neurophysiological techniques provides support for these functional relationships, showing exercise and aerobic fitness level to be associated with profound changes in sensory, motor and autonomic regions of the brain (Kramer and Erickson, 2007), alongside larger regional brain volumes (Tseng et al., 2013), reinforced neural networks (Nakata et al., 2010) and increased neuroplasticity (Knaepen et al., 2010).

There are a number of narrative, systematic and meta-analytic reviews assessing the relationship between acute exercise and cognition (Brisswalter et al., 2002, Chang et al., 2012, Etnier et al., 1997, Etnier et al., 2006, Kashihara et al., 2009, Lambourne and Tomporowski, 2010, Tomporowski and Ellis, 1986, Tomporowski, 2003). Despite advances in our understanding however, a consensus in this area is lacking. For example, studies have found positive effects (Hogervorst et al., 1996, McMorris and Graydon, 1997a), negative effects (Chmura et al., 1998, Fery et al., 1997) and no effects (Bard and Fleury, 1978, McMorris and Graydon, 2000) of exercise on cognitive function. Literature reviews have proposed that these conflicting results are due to a number of moderating variables that influence the exercise-cognition relationship; consequently, conclusions on the overall effect of exercise on cognition can only be drawn when moderators are controlled. Indeed, this highlights the complex relationship between exercise and cognitive function and thus, alongside broad all-encompassing reviews and analyses, there is a need for more detailed systematic reviews to help articulate the effects of exercise on cognitive function within explicit parameters.

Two recent meta-analyses highlight a number of influential moderating factors that require control in research examining the relationship between exercise and cognition: (i) exercise intensity, (ii) exercise duration, (iii) exercise mode, (iv) cognitive task type, (v) participant fitness, (vi) timing of cognitive task administration and (vii) the rigor of the study design (Chang et al., 2012, Lambourne and Tomporowski, 2010). Surprisingly the number of intervention trials that have examined the relationship between high-intensity exercise (HIE) and cognition are relatively small, especially when compared to the wealth of research investigating the effect of low- and moderate-intensity exercise on cognitive function (Chang et al., 2012, Davranche and McMorris, 2009, Joyce et al., 2009, Kashihara et al., 2009, McMorris et al., 2011). It is generally accepted that moderate intensity exercise promotes positive changes in cognitive function (Chang et al., 2012, Tomporowski, 2003), while a consensus on the effect of HIE is yet to be reached.

High-intensity exercise initiates significant metabolic, mechanical and biochemical disturbances both peripherally and centrally. These disturbances include a significant disruption to intramuscular homeostasis (Tomlin and Wenger, 2001), a disproportionate increase in the rate of peripheral fatigue development (Burnley et al., 2012) and an increase in the release of catecholamines such as adrenaline and noradrenaline (McMorris et al., 2015). The large increase in adrenaline and associated arousal, has led to much research investigating the inverted-U effect, which postulates that once an ‘optimal point’ is reached, any further increase in metabolic load will be detrimental to cognitive performance (McMorris, 2016). Despite this theory setting a general notion that HIE has detrimental effects on cognition, empirical studies have not observed a clear relationship (Tomporowski, 2003).

Though there is evidence supporting an inverted-U effect (Aks, 1998, Brisswalter et al., 1995, Chmura et al., 1994, McMorris and Graydon, 2000, Reilly and Smith, 1986), this function is not always observed in trained individuals with higher fitness levels (Hüttermann and Memmert, 2014, Pesce, 2009a). Consequently, one of the main methodological problems often proposed to explain the diversity of experimental results is the failure to control for physical fitness (Brisswalter et al., 2002, Tomporowski, 2003). In support of this, neuroimaging studies have shown greater metabolic workloads require increased brain activation of the motor cortices which come at the expense of other brain regions due to limited resource capacity (Dietrich and Sparling, 2004). This observation suggests that the influence of physical exercise on cognitive processes may be mediated by the level of activation induced by physical exertion. Within this framework it is suggested that greater fitness levels and

familiarity with greater metabolic workloads might enable greater resource allocation for cognitive tasks, thus facilitating cognitive performance (Brisswalter et al., 2002).

Trained individuals from various backgrounds such as sports, the military and emergency services regularly engage in situations where they must respond quickly and make critical decisions during and following exposure to strenuous physical workloads. The ability to maintain cognitive performance on such occasions is paramount and thus prior to providing any recommendations, an increased understanding within this area is required to establish a clear effect. The limited number of studies investigating HIE and cognition is surprising, especially considering the indication of detrimental effects. Furthermore, the need for more reviews to control moderators is emphasized when the impact of these moderators on the acute exercise-cognition relationship is considered. Adding more focus to these reviews via this method will enable the provision of more detailed conclusions regarding the effect of different exercise intensities on cognitive domains in specific populations. Thus, it is the purpose of this systematic review to critically assess the effect of acute HIE on cognitive function in trained individuals. In relation to the first objective of the thesis, this study aims to identify and evaluate current understanding concerning the effects of strenuous exercise on cognitive performance in trained populations.

2.2 Method

This systematic review was performed following Cochrane Collaboration recommendations and criteria (Higgins and Green, 2011), which are in line with guidelines from the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement (Moher et al., 2009).

2.2.1 Eligibility criteria

PICO (population, intervention, comparison, and outcome) criteria were used to determine eligibility for this review. Accordingly, the following inclusion criteria were applied: studies included trained/highly fit participants; HIE was the independent variable; a control and/or comparison group was used; performance on a general laboratory cognitive task was the dependent variable; and cognitive tests were administered either during or ≤10 minutes following exercise cessation. Included studies were designed to test the effect of high-intensity exercise (intervention) on cognitive task performance (outcome); consequently, studies were not included if

exercise was not the main intervention (i.e. assessment of pharmacological or nutritional interventions). In addition, only full-text original studies written in English were included.

2.2.1.1 Trained/highly fit participants: Definition

When aerobic fitness was provided, a population was deemed trained if they could be classified as having 'excellent' or 'superior' fitness according to the ACSM guidelines (Pescatello, 2014). This provided an age and gender adjusted criteria for inclusion. When aerobic fitness was not provided, inclusion was based upon the description of the sample provided by the author(s). Studies were included if they examined at least one trained group; if studies examined low/moderately fit participants but compared them to a trained group, they were included.

2.2.1.2 High-intensity exercise: Definition

In line with previous reviews, an 'acute' exercise period was defined as "exercise performed within a single day" (Chang et al., 2012). Consistent with the definitions used by McMorris et al. (2015), HIE was defined as exercise ≥ 80 % maximum power output (W_{max}). If W_{max} values were not reported but $\dot{V}O_{2max}$ or percentage maximum heart rate ($\%HR_{max}$) were, the conversion formula provided by Arts and Kuipers (1994) was used to determine eligibility: $\%\dot{V}O2_{max} = 12.1 + 0.866 \times \%W_{max}$, percentage $HR_{max} = 46.3 + 0.545 \times \%W_{max}$. This procedure has previously been applied by both McMorris and Hale (2012) and Schapschroer et al. (2016). If other indicators of intensity were provided e.g. RPE or percentage heart rate reserve (% HRR), the exercise physiology literature was examined to ascertain whether or not the intensity was sufficient to qualify for inclusion. Exercise was deemed high-intensity when exercise went to voluntary exhaustion or when maximal effort was required. Where exercise was intermittent, duration and time working at high-intensities were used to determine eligibility.

2.2.2 Information sources and search strategy

The search strategy included several steps to ensure all possible relevant articles were obtained. First, an online search of electronic databases was conducted. To build the search criteria for database searches a PICO search strategy was employed (Higgins and Green, 2011); an example of the strategy can be seen in Table 2.1. To

avoid database bias, searches were conducted on seven different electronic databases: Academic Search Complete; PsycARTICLES; PsycINFO; PubMed; Scopus; SPORTDiscus; and Web of Science. In addition, reference lists within retrieved articles were manually reviewed as well as reference lists from previous reviews relevant to the exercise and cognition literature (Chang et al., 2012, Etnier et al., 1997, Lambourne and Tomporowski, 2010, McMorris and Hale, 2012, Schapschröer et al., 2016, Tomporowski, 2003, Tomporowski and Ellis, 1986). Electronic database searches were carried out on the 4th February 2017 and studies published anytime until the day of searching were considered.

2.2.3 Study selection and data collection process

Two researchers independently screened for initial exclusion via titles and abstracts. If it was unclear whether a study met the inclusion criteria, a secondary exclusion was conducted based on a review of full-text articles. If the full-text was not available, first authors were contacted to obtain the manuscript. Full-text articles were independently scanned by two researchers to determine whether they met the inclusion criteria. Any disagreements were resolved by discussion and if an agreement could not be attained, inclusion was decided by a third researcher. The data collection process is presented in Figure 2.1.

Table 2.1 Example of PubMed search strategy

Concept Search Strategy	Line	Entry
Trained individuals	1	Trained
	2	Athlete*
	3	Skill*
	4	Expert
	5	Recreational athlete
	6	1or2or3or4or5
Exercise intensity	7	Strenuous exercise
	8	High intensity exercise
	9	Physical exertion
	10	Physical load
	11	Fatiguing exercise
	12	7or8or9or10or11
Cognitive function	13	Cogniti*
	14	Executive function
	15	Memory
	16	Psychomotor
	17	Reaction time
	18	Attention
	19	Decision making
	20	13or14or15or16or17or18or19
	21	6and12and20

2.2.4 Quality assessment

All studies included in the review were subject to quality assessment as suggested by the Cochrane guidelines (Higgins and Green, 2011). The quality of the studies was assessed by two members of the study team (SB and MF) who graded them with respect to their methodological strength using the quantitative assessment tool 'QualSyst' (Kmet et al., 2004). To assess scientific rigour, QualSyst assesses 14 items that are scored depending on the degree to which the specific criteria were met (yes = 2, partial = 1, no = 0) (Table 2.2). Items not applicable to a particular study

design were marked ‘N/A’ and excluded from the calculation of the summary score. The total sum of all relevant items was divided by the total possible score to give each study a final summary score. Quality assessment was completed by two researchers independently; disagreements were solved by consensus or by a third researcher. As outlined in the QualSyst guidelines, a final summary score of ≥75 % indicated strong quality, a score of 55-74 % indicated moderate quality and a score ≤54 % indicated weak quality.

2.2.5 Analysis

Cognitive tasks were identified based upon the particular test that was administered and were subsequently classified into a general cognitive task category (dependent variable). Since only a few tests measure a single cognitive construct (Lezak, 2004) two of the most well-established compendiums for neuropsychological assessment were used to identify and categorize tasks (Lezak, 2004, Strauss et al., 2006). Both of these resources have been used for similar purposes in previous reviews (Chang et al., 2012, Roig et al., 2013) and provide precise definition and categorization of cognitive tests into different domains. Each cognitive task and the time the task was completed (i.e. during and/or immediately post-exercise) was classified as an outcome measure and the number of outcome measures were tallied. Consistent with similar reviews, the direction of each outcome measure was coded as positive (+), negative (-), no effect (o).

Table 2.2 Quality assessment (Kmet et al., 2004)

Study	Question described	Appropriate study design	Appropriate study selection	Characteristics described	Random allocation	Researchers blinded	Subjects blinded	Outcome measures well defined and robust to bias	Appropriate sample size	Analytic methods well described	Estimate of variance reported	Controlled for confounding	Results reported in detail	Conclusion supported by results	Rating
Brisswalter	2	2	2	2	0	N/A	N/A	2	1	2	2	0	2	2	79%
Bue-Estes	2	2	2	2	0	N/A	N/A	2	1	2	2	1	2	2	83%
Draper	2	2	1	1	N/A	N/A	N/A	2	1	2	2	0	2	2	77%
Guizani[a]	2	2	2	2	2	N/A	N/A	2	1	2	2	0	2	2	88%
Guizani[b]	2	2	2	2	1	N/A	N/A	2	1	2	2	0	2	2	83%
Labelle	2	2	2	2	N/A	N/A	N/A	2	2	2	2	1	2	2	95%
Reilly	2	2	2	1	0	N/A	N/A	2	1	2	2	0	1	1	67%
Smith	2	2	2	1	0	N/A	N/A	2	2	2	2	1	2	2	83%
Tomporowski	2	2	1	2	0	N/A	N/A	2	1	0	1	0	1	2	58%
Whyte	2	2	2	2	2	N/A	N/A	2	2	2	2	1	2	2	96%

2 indicates yes, 1 indicates partial, 0 indicates no, NA not applicable.

Quality scores: ≥75 % strong, 55 ≥ 74 % moderate, ≤54 % weak

2.3 Results

2.3.1 Study selection

Each step of the systematic search with the number of studies reviewed at each stage and main reasons for exclusion are shown in Figure 2.1 below.

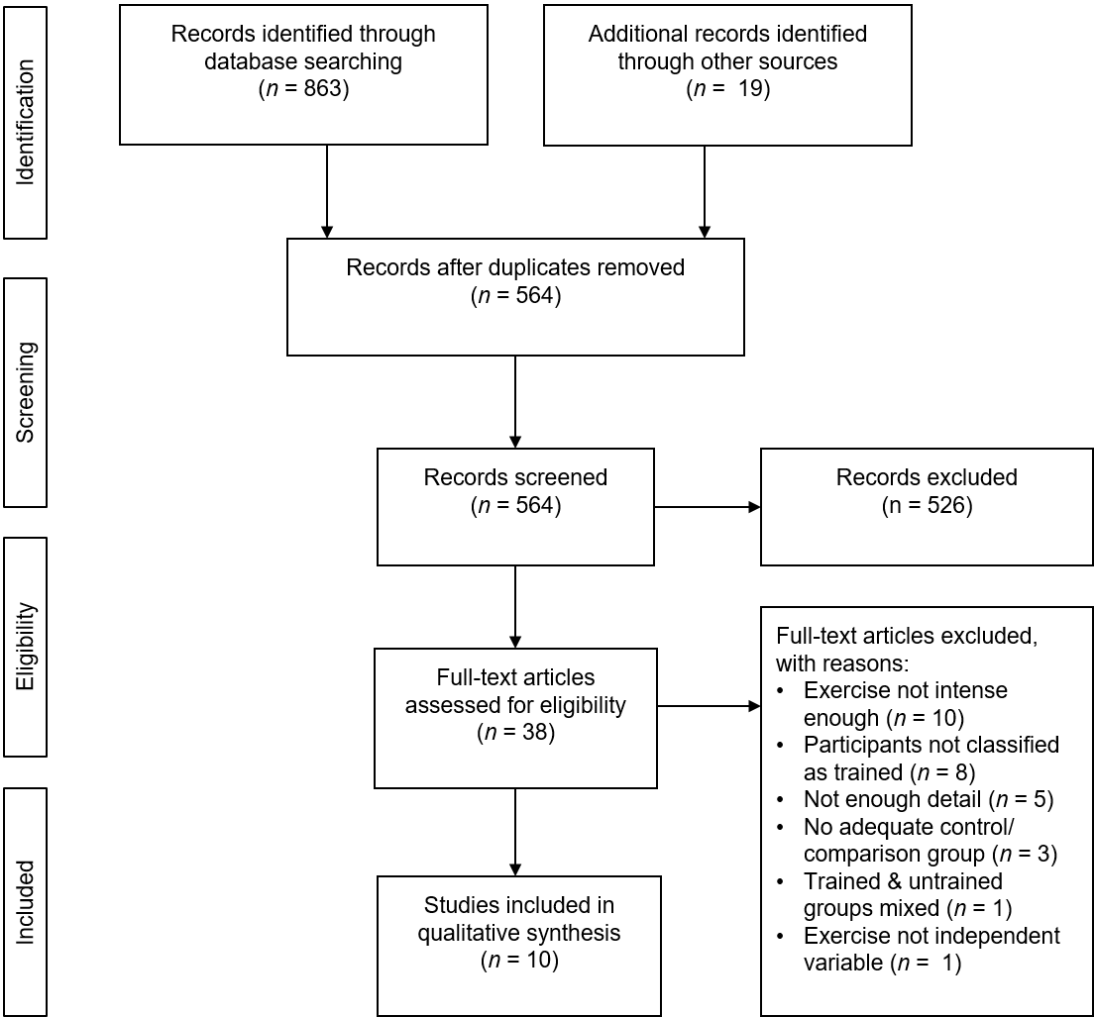

Figure 2.1 PRISMA flowchart illustrating the literature search and selection process at each stage; from (Moher et al., 2009)

A total of 863 articles were located through the systematic search; of these 318 were duplicates and therefore removed. An additional 19 articles were identified from additional records including relevant reviews and hand-searching through the

reference lists of the articles found through the database search. A total of 564 articles were screened by title and abstract leading to the exclusion of 526 articles which did not meet the inclusion criteria. The main reasons for exclusion included: “cognitive performance not being the dependent variable”, “exercise not being the independent variable”, “cognitive tasks not being general laboratory-based tasks” and “studies examining injuries or diseases”. The remaining 38 articles were assessed for inclusion by reading the full-text; this resulted in a further 28 articles being excluded. The primary reason for exclusion was the exercise intervention not meeting the required intensity (Del Percio et al., 2009, Elsworthy et al., 2016, Hancock and McNaughton, 1986, Hogervorst et al., 1996, Hüttermann and Memmert, 2014, Lemmink and Visscher, 2005, Pesce et al., 2007, Pesce and Audiffren, 2011, Pesce et al., 2011, Sjöberg, 1980). Several studies were excluded because participants did not meet the ‘trained’ criteria (Aks, 1998, Fery et al., 1997, Fleury and Bard, 1987, Fleury et al., 1981a, Levitt and Gutin, 1971, McMorris and Keen, 1994, Thomas et al., 2016, Wang et al., 2013). Five studies did not provide enough detail to enable inclusion with regards to either trained status (Malomsoki and Szmodis, 1970, Nibbeling et al., 2014, Strauss and Carlock, 1966) or exercise intensity (Guizani et al., 2006c, Reddy et al., 2014). Three studies did not provide an adequate control or comparison group (Chmura et al., 1994, Luft et al., 2009, Thomson et al., 2009). One study mixed trained and untrained participants in the intervention groups (Tsorbatzoudis et al., 1998) and exercise in one study was not the main independent variable (Coco et al., 2009). A total of 10 studies remained and were included in the review.

2.3.2 Descriptive characteristics of included studies

The characteristics of the studies regarding participants, exercise interventions and cognitive tests are shown in Table 2.3. Overall, the data from 130 participants (101 male, 29 female) who met the ‘trained’ criteria were included in this review. Mean age ranged from 19-31 years (mean 23.3 ± 2.6 years) and from the seven studies that provided specific information regarding the fitness level of the participants, mean $\dot{V}O_{2max}$ values was 57.5 $ml \cdot kg^{-1} \cdot min^{-1}$ (mean range 50.6 to 66.0 $ml \cdot kg^{-1} \cdot min^{-1}$). Nine studies used participants involved in sports including running, triathlon, soccer, hockey, athletics, fencing, rugby, Gaelic football and hurling. Only two modes of exercise were used in study protocols with cycling being the most common (n = 6)

followed by running (*n* = 4); the average exercise time at high-intensity was 5.6 ± 3.0 minutes with the range being from 1-10 minutes.

In total, 5 studies used a mixed between-subjects and within-subjects design, 3 studies used a within-subject's crossover design and 2 used an independent between-subjects only design. Seven studies compared HIE to moderate- and low-intensities (Brisswalter et al., 1997, Draper et al., 2010, Guizani et al., 2006b, Labelle et al., 2013, Lo Bue-Estes et al., 2008, Reilly and Smith, 1986, Smith et al., 2016a); of these 5 studies included a rest condition (Brisswalter et al., 1997, Draper et al., 2010, Guizani et al., 2006b, Lo Bue-Estes et al., 2008, Smith et al., 2016a) with 2 failing to counterbalance the order of the rest or exercise intensities (Guizani et al., 2006b, Lo Bue-Estes et al., 2008). The 3 remaining studies did not compare HIE to other intensities but instead investigated one HIE session and compared this to a rest condition (Llorens et al., 2015) or non-exercising group implementing counterbalanced (Whyte et al., 2015) and non-counterbalanced orders (Tomporowski et al., 1987).

Table 2.3 Summary of studies examining the effect of high-intensity exercise on cognitive performance

Author	Design	Participants	Exercise		Cognitive Performance Outcome			Main results	Comments
			Type & Intensity	Time at HI	Task	General Category	Time of testing		
Brisswalter et al. (1997)	Mixed	**Trained: *n* = 10** A = 23.3 ± 1.5 M/F = 10/0 $\dot{V}O_2$ = 64.1 ± 2.3 **Untrained: *n* = 10** A = 23.7 ± 1.8 M/F = 10/0 $\dot{V}O_2$ = 42.2 ± 3.0	**Cycle ergometer** 20%, 40%, 60%, 80% W_{max}	10 min	SRT	Information processing	Pre, Post & during	No effect on speed or accuracy during or post HI exercise in trained group compared to lower intensity exercise	Rest condition Counterbalanced order
Draper et al. (2010)	Crossover	**Trained: *n* = 12** A = 31.5 ± 5 M/F = 12/0 $\dot{V}O_2$ = NR	**Cycle ergometer** 80% VT, 25% Δ VT, 75% Δ VT	3 min + time of task	SRT, CRT	Information processing	During	Speed: Faster CRT during HI exercise (75% Δ VT) compared to rest. No effect on movement time or total response time for SRT or CRT Accuracy: No effect of HI exercise on SRT or CRT compared to rest.	Rest condition Counterbalanced order Speed assessed as RT, movement time & total response time; considered as 6 outcome measures.
Guizani et al. (2006b)	Mixed	**Trained: *n* = 12** A = 19.0 ± 2.9 M/F = NR $\dot{V}O_2$ = 50.7 ± 5.6 **Untrained: *n* = 12** A = 20.8 ± 3.9 M/F = NR $\dot{V}O_2$ = 36.9 ± 4.6	**Cycle ergometer** 20%, 40%, 60%, 80% W_{max}	6 min	SRT, CRT	Information processing	During	Speed: Faster CRT at 80% W_{max} in trained group compared to rest. No effect on SRT. Accuracy: No effect of HI exercise compared to rest.	Rest condition No Counterbalanced order Simple effects analyses were conducted despite no interaction.

Table 2.3 Summary of studies examining the effect of high-intensity exercise on cognitive performance (continued)

Author	Design	Participants	Exercise		Cognitive performance outcome			Main results	Comments
			Type & intensity	Time at HI	Task	General category	Time of testing		
Labelle et al. (2013)	Mixed	**Trained: *n* = 16** A = 24.6 ± 2.5 M/F = 9/7 $\dot{V}O_2$ = 50.6 ± 7.9 **Untrained: *n* = 21** A = 23.2 ± 2.6 M/F = 10/11 $\dot{V}O_2$ = 38.3 ± 5.2	**Cycle ergometer** 40 %, 60 %, 80 % W_{max}	6.5 min	Stroop task	Executive function	During	No effect of HI exercise in trained group for speed or accuracy compared to lower intensities or untrained group	No rest condition Counterbalanced order
Llorens et al. (2015)	Mixed	**Trained: *n* = 14** A = 19-28 M/F = 14/0 $\dot{V}O_2$ = 58.4 ± 3.0 **Untrained: *n* = 13** A = 19-28 M/F = 13/0 $\dot{V}O_2$ = 41.3 ± 6.3	**Cycle ergometer** Incremental test to exhaustion	NR	Spatial attention task	Attention	Post	Speed: Faster RT after exercise in trained group compared to rest condition. Accuracy: No effect	Rest condition Counterbalanced order
Lo Bue-Estes et al. (2008)	Mixed	**Trained: *n* = 9** A= 20.8 ± 0.9 M/F = 0/9 $\dot{V}O_2$ = 55.3 ± 7.9 **Control: *n* = 8** A = 21.1 ± 2.2 M/F = 0/8 $\dot{V}O_2$ = NR	**Treadmill** 25 %, 50 %, 75 %, 100 % $\dot{V}O_{2max}$	1 min	SRT, CPT, CS, WM, VSM, CSD.	Information processing, Attention, Memory	Pre, Post & during	No change post-exercise in SRT, CPT, CS, VSM or CSD. Negative effect of HI on working memory at 100 % $\dot{V}O_2$ & post-exercise compared to pre-exercise.	Rest group (control) No counterbalanced order Experimental group mean scores adjusted using control group mean scores on complex cognitive tasks. WM only test done 'during' exercise. All but SRT measured as throughput from the ANAM; a measure of correct hits (accuracy) in a set period of time.

Table 2.3 Summary of studies examining the effect of high-intensity exercise on cognitive performance (continued)

Author	Design	Participants	Exercise		Cognitive performance outcome			Main results	Comments
			Type & intensity	Time at HI	Task	General category	Time of testing		
Reilly and Smith (1986)	Crossover	**Trained: *n* = 10** A = 20.0 ± 0.8 M/F = 10/0 $\dot{V}O_{2max}$=57.6 ± 7.7	**Cycle ergometer** 10 %, 25 % 40 % 55 %, 70 %, 85 % $\dot{V}O_{2max}$	NR	Pursuit rotor task	Information processing	During	Reduced performance at 85 % $\dot{V}O_2$ compared to control (10 % $\dot{V}O_2$)	No rest condition (10 % $\dot{V}O_2$ used as control) Counterbalanced order
Smith et al. (2016a)	Crossover	**Trained: *n* = 15** A= 28.0 ± 5.0 M/F = 6/9 $\dot{V}O_{2max}$ = NR	**Treadmill** 70% HRR (until RPE 15-17) and 90 % HRR (until RPE 18-19)	~4 min	Go/No-go	Executive function	During	Speed: Slower RT during high-intensity exercise compared to rest and moderate-intensity Accuracy: Higher omission and decision errors during high-intensity exercise compared to rest and moderate-intensity	Rest condition Counterbalanced order Accuracy provided 2 outcome measures split into omission and decision error rate
Tomporowski et al. (1987)	Between-subjects	**Trained: *n* = 12** A= 19-23 M/F = 8/4 $\dot{V}O_{2max}$=66.0 ± NR **Untrained: *n* = 12** A= 17-29 M/F = 8/4 $\dot{V}O_{2max}$=41.1 ± NR	**Treadmill** Incremental up to 80 % $\dot{V}O_{2max}$	NR	Free-recall memory	Memory	Post	No effect of exercise on free-recall memory compared to untrained group	No rest condition No counterbalanced order Intensity of exercise was based on HR corresponding to % $\dot{V}O_2$

Table 2.3 Summary of studies examining the effect of high-intensity exercise on cognitive performance (continued)

Author	Design	Participants	Exercise		Cognitive performance outcomes			Main results	Comments
			Type & Intensity	Time at HI	Task	General category	Time of testing		
Whyte et al. (2015)	Between-subjects	**Trained: *n* = 20** A = 21.1 ± 1.3 M/F = 20/0 $\dot{V}O_{2max}$ = NR **Control: *n* = 20** A = 21.2 ± 1.3 M/F = 20/0 $\dot{V}O_{2max}$ = NR	**Intermittent Running & Jumping** Until RPE ≥18	~6 min	SDMT, Stroop	Attention, Executive function	Pre & Post	Reduced Stroop performance post-exercise compared to the control group. No change in SDMT performance post-exercise in either group.	Rest group (control) Counterbalanced order Average % of HR_{max} during exercise = 94.6 %

A= age; ANAM = Automated Neuropsychological Assessment Metrics; CPT = continuous processing task; CRT = choice reaction time; CS = code substitution; CSD = code substitution delay; HI = high-intensity; HR_{max} = heart rate maximum; HRR = heart rate reserve; M/F = male/female; Mixed = mixed between and within subjects design; *n* = number of subjects; NR = not reported; RPE = rate of perceived exertion; RT = reaction time; SDMT = symbol digits modality test; SRT = simple reaction time; $\dot{V}O_{2max}$ = maximal oxygen consumption; VSM = visuospatial memory; VT = ventilatory threshold; W_{max} = maximum power output; WM = working memory; Δ = the difference between VT and $\dot{V}O_{2max}$; ~ = approximately. Age is provided as mean ± standard deviation or range. $\dot{V}O_2$ value are normalised to body weight ($mL \cdot kg^{-1} \cdot min^{-1}$). Counterbalanced order refers to exercise intensity. Only data from trained participants outlined in the table were included in the analysis

2.3.3 Effect of acute high-intensity exercise on cognitive function

Results for the effect of HIE on cognitive performance in trained groups are presented in Table 2.4. In total, 4 cognitive domains were assessed across 10 studies with some studies assessing more than one domain. Reaction time and information processing were combined under the category 'information processing' and were regarded as simple cognitive tests. Executive function, attention and memory were considered complex.

2.3.3.1 Information processing

Five studies assessed information processing; of these 4 used RT tasks and 1 used a pursuit rotor task. RT was assessed via SRT and CRT in 4 studies (Brisswalter et al., 1997, Draper et al., 2010, Guizani et al., 2006b, Lo Bue-Estes et al., 2008). In all 4 studies, HIE was found to have no effect on speed or accuracy of SRT performance. CRT was assessed in 2 of these 4 studies (Draper et al., 2010, Guizani et al., 2006b) and in both, an improvement in speed of CRT was observed following HIE. In contrast, the 1 remaining study assessed information processing using a pursuit rotor task (Reilly and Smith, 1986) and found a negative effect of exercise. In total, there were 18 outcome measures, 11 measuring speed and 7 measuring accuracy. Overall, no effect of HIE on speed or accuracy was observed on the majority of outcome measures.

2.3.3.2 Executive function

Of the 10 studies included, 3 assessed executive function. Labelle et al. (2013) measured both speed and accuracy on a Stroop task during exercise providing 2 outcome measures which showed no effect of HIE. Similarly, Whyte et al. (2015) also used a Stroop task but administered the test pre-and post-exercise and measured correct responses (regarded as accuracy) only. These results demonstrated a reduced performance following HIE. Smith et al. (2016a) used a Go/No-go task to measure speed and two types of accuracy (omission and decision errors) providing 3 outcome measures which all showed a deterioration in cognitive performance during HIE. A total of 6 outcome measures were provided for executive function. Overall 4 outcome measures found negative effects of HIE on executive function while 2 found negligible effects.

2.3.3.3 Memory

Two studies assessed memory. Lo Bue-Estes et al. (2008) assessed memory using an Automated Neuropsychological Assessment Metrics (ANAM) cognitive testing system. Results from the ANAM (throughput) provide a corrected response rate measuring the number of correct responses in a set period of time; due to the nature of the task and to align these results with that of others, this review has regarded throughput as accuracy. Four domains of memory (short-term memory, long-term memory, VSM, WM) were assessed post-exercise. In addition, WM was assessed during, as well as post-exercise, providing a total of 5 outcome measures. All tasks other than WM showed no effect of HIE. WM was negatively affected during exercise at 100 % $\dot{V}O_{2max}$ and immediately following HIE when compared to the pre-exercise rested state. Tomporowski et al. (1987) on the other hand assessed free-recall memory post-exercise at 80 % $\dot{V}O_{2max}$ and found no effect of exercise on memory compared to an untrained group. Overall, 4 outcome measures for memory found no effect of HIE whilst 2 found negative effects.

2.3.3.4 Attention

Three studies assessed attention following HIE. Lo Bue-Estes et al. (2008) used a continual processing task assessing accuracy (as throughput from the ANAM) and found no effect. Llorens et al. (2015) used a spatial attention task assessing both speed and accuracy and similarly found no effect of HIE on accuracy performance though a positive effect was observed on RT. Whyte et al. (2015) employed a symbol digit modality test (SDMT) to assess correct responses (regarded as accuracy) following a high-intensity intermittent running and jumping protocol. The results of this study indicated no effect of HIE on SDMT accuracy. In total 4 outcome measures were provided. No effect was found for accuracy whilst one positive effect was observed for speed.

2.3.3.5 Time of testing

The time at which cognitive tasks were administered presents one of the main methodological differences between studies. When assessing the effect of acute exercise on cognitive function, tasks can be administered during and/or after the cessation of exercise. Within the 10 studies included, 5 studies assessed cognitive function during exercise (Draper et al., 2010, Guizani et al., 2006b, Labelle et al.,

2013, Reilly and Smith, 1986, Smith et al., 2016a), 2 studies performed tasks both during and pre-post exercise (Brisswalter et al., 1997, Lo Bue-Estes et al., 2008), one study performed tasks before and immediately following exercise (Whyte et al., 2015) and the remaining two studies performed cognitive tasks post-exercise only (Llorens et al., 2015, Tomporowski et al., 1987). There was no obvious pattern of a time-related effect on any cognitive domain. However, there were fewer outcome measures for post-exercise compared to during; consequently, this review cannot establish any clear conclusions regarding the time of testing.

Table 2.4 Effects of high-intensity exercise on each cognitive task category

Cognitive task category	Studies	Total outcome measures	Outcome measures Post			Outcome measures During		
			+	o	-	+	o	-
Information processing								
Speed	*n* = 4	*n* = 11	-	*n* = 2	-	*n* = 2	*n* = 7	-
Accuracy	*n* = 4	*n* = 7	-	*n* = 1	-	-	*n* = 5	*n* = 1
Executive function								
Speed	*n* = 2	*n* = 2	-	-	-	-	*n* = 1	*n* = 1
Accuracy	*n* = 3	*n* = 4	-	-	*n* = 1	-	*n* = 1	*n* = 2
Memory								
Speed	*n* = 0	*n* = 0	-	-	-	-	-	-
Accuracy	*n* = 2	*n* = 6	-	*n* = 4	*n* = 1	-	-	*n* = 1
Attention								
Speed	*n* = 1	*n* = 1	*n* = 1	-	-	-	-	-
Accuracy	*n* = 3	*n* = 3	-	*n* = 3	-	-	-	-
Totals	*n = 19*	*n = 34*		*n* = 13			*n* = 21	
			8 %	77 %	15 %	10 %	67 %	24 %

2.4 Discussion

This focussed review set out with a specific aim to identify and evaluate current understanding concerning the effects of HIE exercise on cognitive function in trained populations. Overall the majority of studies included suggested that neither speed nor accuracy are influenced in tasks requiring simple cognitive processing during or following a single-bout of HIE in trained individuals. However, the results regarding complex cognitive processes are more ambiguous. These results support others that emphasize the importance of considering the specific cognitive task type that is being

assessed when synthesising results, as the influence of exercise on cognition has been shown to be dependent on the specific cognitive domain that is being assessed (Lambourne and Tomporowski, 2010, McMorris, 2016).

Of the cognitive domains assessed, information processing requires substantially less neural activity and brain resource than complex tasks (McMorris and Hale, 2012). Within the information processing domain, RT (SRT and CRT) was most commonly assessed, with 4 studies measuring a total of 18 outcome measures for both speed and accuracy. Reaction time is a popular measure in the literature on acute exercise and cognition, particularly in studies designed to assess the inverted-U effect (Lambourne and Tomporowski, 2010). Moreover, RT on simple tasks has previously been shown to be sensitive to the effects of acute exercise (Tomporowski, 2003). In the most recent comprehensive meta-analysis on acute exercise and cognition, Chang et al. (2012) found no significant effect of exercise on SRT or CRT; this effect however was averaged over a range of exercise intensities, leading the authors to suggest there may have been an influence of exercise intensity on RT that was undetected. The current review, however, found no effect on speed of RT in 9 of the 11 observed outcome measures. Interestingly, the 2 remaining outcome measures were from the only 2 studies included in the review that assessed CRT, with both of these studies observing a positive effect of HIE on speed of CRT (Draper et al., 2010, Guizani et al., 2006b). This supports the conclusions of Draper et al. (2010) whose results indicate that SRT and CRT are affected differently by exercise and should be considered individually. Due to the limited number of studies in this review, all RT measures were considered as a whole as organised by Lezak (2004). To establish more evidence for differential effects on these two tasks, more research is required.

Collectively, the lack of effect observed for information processing tasks disagrees with the results of Lambourne and Tomporowski (2010) and fails to support studies that have observed an inverted-U effect (Brisswalter et al., 1995, Chmura et al., 1994, Salmela, 1986). A potential reason for this effect, and an important criterion within this review, is the high/trained fitness level of participants. Narrative (Brisswalter et al., 2002, Tomporowski, 2003) and meta-analytic (Chang et al., 2012, Etnier et al., 1997, McMorris et al., 2011, McMorris and Hale, 2012) reviews have highlighted physical fitness as a key moderator of the exercise-cognition relationship and it has been hypothesised that trained individuals may be able to compensate for the negative effects of fatigue at high exercise intensities (Tomporowski and Ellis, 1986). Proposed mechanisms by which this may happen include a reduction in the magnitude of change in brain metabolism and functioning during exercise (Llorens et

al., 2015) and more efficient allocation of attentional resources (Kamijo et al., 2010, Polich and Kok, 1995). As HIE is typically associated with negative effects on cognitive performance (Fery et al., 1997, Kamijo et al., 2010, McMorris et al., 2009, McMorris and Rayment, 2007), the results may suggest trained individuals are able to maintain cognitive performance on tasks of information processing at higher levels of arousal (Brisswalter et al., 1997). Alternatively, Tomporowski and Ellis (1986) suggest that cognitive tasks without challenge that do not require enough attentional resources, do not show any effect of exercise on cognitive function. This may imply that the trained participants included in this review did not perceive simple tasks of RT and information processing challenging, resulting in the lack of effect.

Largely, the results for accuracy on information processing tasks indicate no effect of HIE, supporting previous findings from both McMorris and Hale (2012) and Schapschroer et al. (2016). This result is surprising considering evidence, particularly in sporting conditions, demonstrating reductions in whole-body psychomotor skill accuracy with fatiguing physical exertion (Russell and Kingsley, 2011). One suggestion has indicated the likelihood of a ceiling effect for accuracy in healthy individuals when assessed in tasks such as RT (McMorris, 2016). Moreover, it is possible that consistent failures to observe accuracy effects is due to the nature of the cognitive tasks. Many cognitive tasks assessing both simple and complex cognitive processes have been designed to measure performance through speed of processing, with accuracy measures merely there to safeguard against the speed-accuracy trade off (McMorris and Hale, 2012). If accuracy is to be validly assessed, it is argued that tests must be used that control participants focus on solving the tasks with a reduced emphasis on speed. Interestingly, when accuracy is assessed via whole-body psychomotor skills, such as those performed in sporting situations, heavy exercise has been found to have a large effect (McMorris et al., 2015). This may potentially indicate that the diminishing accuracy observed with increasing levels of fatigue during sporting situations may be due to detriments to neurophysiological mechanisms rather than cognitive components. Deciphering the extent to which precise areas contribute to reductions in whole-body performance provides a challenging but important task for future research.

Higher-order cognitive processes are described as those central executive processes involving several functions including planning, scheduling, working memory, multi-tasking, cognitive flexibility and abstract thinking (Hillman et al., 2008, McMorris and Hale, 2012). These functions are heavily dependent on the activation of the PFC which constitutes the highest level of cortical hierarchy (Fuster, 2001). Compared to

the lower-order, simpler cognitive tasks assessed in this review, the impact of HIE on higher cognitive processes is ambiguous. As a whole, 6 studies assessed executive function, attention and memory providing a total of 16 outcome measures for both speed and accuracy (Figure 2.2). Attention was assessed by three studies; whilst little can be concluded on speed of attention as it was only assessed by one study, all accuracy outcome measures indicated no difference with HIE. Similarly, the results for memory demonstrated a greater tendency to show no effect of HIE; however, as 5 of the 6 outcome measures were obtained from one study, this review cannot establish any clear conclusions on this cognitive domain. Observations on measures of memory following acute exercise have failed to yield reliable results with some authors suggesting that memory may not be particularly sensitive to the effects of acute exercise (Chang et al., 2012). As demonstrated by Lo Bue-Estes et al. (2008) however, exercise often has diverse effects on different types of memory and thus when assessing this construct, the specific type of memory the task is assessing is an important consideration. The lack of studies assessing higher cognitive functions such as attention and memory with HIE is surprising considering the complex environments that trained individuals, such as athletes and military personnel, are regularly confronted with when under high physical loads. The ability to assess unknown situations and make appropriate decisions relies heavily on central executive processes and thus if strategies to improve decision-making in these situations are to be established, a greater body of research on the effect of high physical loads on cognition is required.

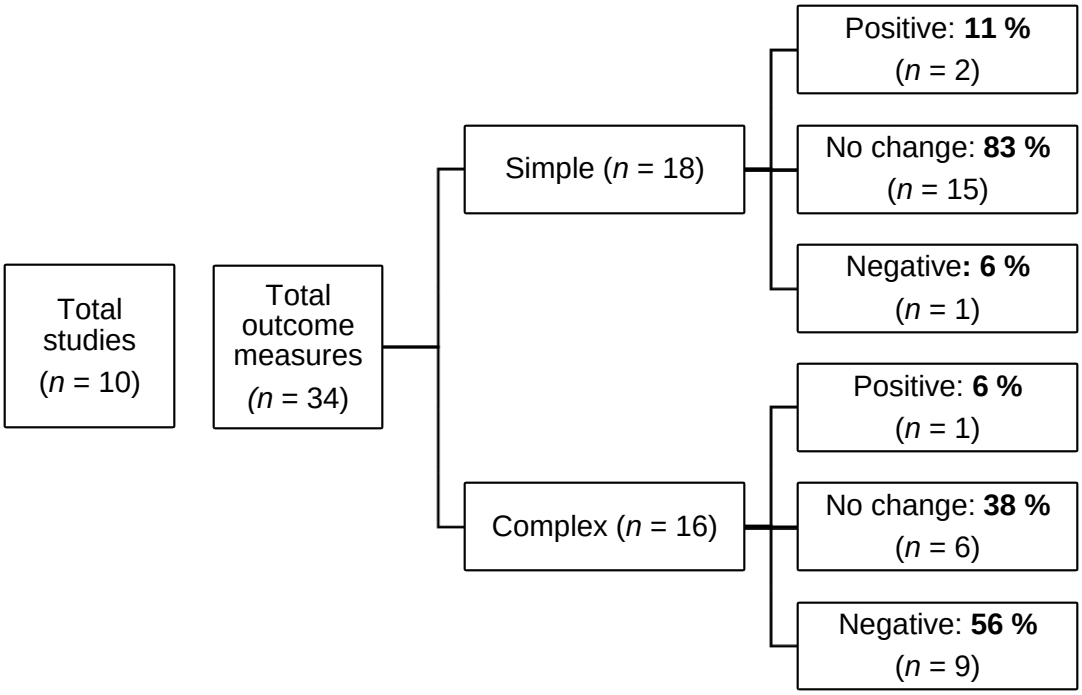

Figure 2.2 Overview of the effect of high-intensity exercise on simple and complex cognitive tasks

Interestingly, measures of executive function have been shown to be particularly sensitive to exercise in general, with effects being significantly larger than other areas of cognitive function (Chang et al., 2012). This is interesting considering that substantial age–related deteriorations of executive function are positively influenced by physical training and fitness (Hillman et al., 2008), potentially suggesting executive function may be particularly sensitive to acute exercise and fitness. Of the complex processes assessed in this review, executive function appeared most sensitive to acute HIE. Whilst caution must be taken with any concluding remarks due to the limited sample of studies, these results do align with previous research suggesting that performance on complex tasks assessing higher-order cognitive processes are more likely to be affected by exercise (Dietrich, 2006, Dietrich and Audiffren, 2011, McMorris and Graydon, 2000). These views have largely been derived from the hypofrontality theory which proposes that HIE causes a change in physiological state, momentarily disrupting brain homeostasis causing a modification in the brains resource allocation (Dietrich, 2003). Based upon this theory, the neural resources used for conducting exercise compete with the same resources necessary to perform cognitive processing. As the maintenance of HIE requires large increases in neural resource demands to sustain activation within the motor and sensory regions, supply

of essential metabolic resources such as oxygen and glucose are reduced to other brain regions (Dietrich and Audiffren, 2011). This reallocation of neural resources results in the temporary inhibition of brain regions not essential to performing exercise, such as areas of the PFC involved in higher-order cognitive functions (Dietrich and Sparling, 2004, Dietrich, 2006).

During the review process of full-text articles there were a number of studies that marginally failed to meet the classification for HIE imposed by this review. The issue surrounding classification of exercise intensity raises an important matter within the exercise literature. Currently there is a lack of consensus on the definition of 'high-intensity' exercise, which has led to the use of a variety of exercise intensities under this categorisation (Hancock and McNaughton, 1986, Hogervorst et al., 1996, Hüttermann and Memmert, 2014). In trying to elucidate the effect of high exercise intensities on cognitive performance, it is essential that consistency be maintained across studies. To maintain consistency and enable comparison of results, the current review classified HIE in line with previous systematic and meta-analytic reviews as ≥80 % W_{max} or equivalent (McMorris et al., 2015, McMorris and Hale, 2012, Schapschroer et al., 2016). High exercise intensities of this nature have been shown to induce substantial metabolic disturbances (Tomlin and Wenger, 2001) alongside large increases in brain concentrations of the neurotransmitters dopamine and noradrenaline (de Vries et al., 2000, Hill et al., 2008, McMorris et al., 2009), and thus distinguish high from moderate and low exercise intensities. Going forward, studies should aim to use consistent terminology when assessing the effect of acute exercise; this will enable comparison of studies and may facilitate a greater consensus within the literature.

Interestingly, the current results are dissimilar to those of a recent review which supported favourable effects of HIE on both general and sport-specific cognitive tasks (Schapschroer et al., 2016). Within this review by Schapschroer et al. (2016) however, only 2 studies investigated the effect of HIE on the performance of general cognitive tasks, both of which were included in the current review (Guizani et al., 2006b, Llorens et al., 2015). In agreement, the 2 respective studies did find positive effects of HIE on cognitive performance. Notably however, these effects were found for speed of performance on CRT tasks, which, as previously stated, requires more evidence to establish differential effects, if any, between SRT and CRT during and/or following exercise. The difference in overall conclusions between both reviews is likely due to methodological differences. Firstly the general conclusions drawn from Schapschroer et al. (2016) encompass both general and sport-specific cognitive

tests. Secondly, Schapschroer et al. (2016) based their review solely on athletic populations. These methodological differences are important considering research surrounding the ‘expert performance approach’, which describes consistently better performance by athletes on sport-specific cognitive tasks (Voss et al., 2009). Consequently, it is argued that measures of fundamental cognitive ability in simulated sport environments are confounded by an athlete’s superior declarative and procedural knowledge. The current review only specified a fitness criterion for inclusion and therefore the type of cognitive task, that is, general rather than sport-specific tasks, was controlled to reduce potential confounding.

2.5 Considerations for future research

An important consideration for further research that has been highlighted in previous reviews is the exercise modality used when performing HIE (Lambourne and Tomporowski, 2010, Schapschröer et al., 2016). The current review highlighted a preference for the use of cycling compared to other modes of exercise. The high number of studies assessing trained individuals on exercise modes that they are not accustomed to is surprising as it reduces ecological validity of the findings (Guizani et al., 2006b, Llorens et al., 2015, McMorris and Graydon, 1996b, McMorris and Graydon, 1997a). Lambourne and Tomporowski (2010) assessed the effect of cycling vs treadmill exercise and found cycling to elicit larger and more positive effects on cognitive performance compared to treadmill running which elicited negative effects. As running requires greater metabolic energy, it is plausible that sensory afferents detecting metabolic disturbance influence the integration of cortical activation and lower the signal-to-noise ratio to a greater extent than cycling exercise, thus resulting in less efficient cognitive processing (Lambourne and Tomporowski, 2010). This highlights an important consideration when designing studies. For example, assessing the effect of exercise on cognition using cycling protocols with soccer players may not provide ecologically valid results. Familiarity with the exercise task has been shown to lower brain modulation and activity, thus freeing more resources for cognitive performance (Brümmer et al., 2011). Where possible studies should consider the accustomed or usual exercise mode of the target population and use this when designing protocols. Notably, the systematic search of the literature found no study that assessed cognitive function following maximal strength exercises. This is surprising considering its relevance to many sports.

A potential shortcoming of the literature as a whole is the use of short duration exercise only. The average exercise duration at high-intensities in the current review was 5.6 minutes. Whilst it is appreciated that exercise at high-intensities cannot be sustained for long periods of time, many sports require intermittent bursts at high-intensities over prolonged periods, or efforts that require the maintenance of a high percentage of $\dot{V}O_{2max}$ for sustained durations. Research using transcranial magnetic stimulation has shown that shorter HIE lasting around 6 minutes results in greater peripheral fatigue, whereas longer durations (>30 minutes) cause greater disturbances in central fatigue (Thomas et al., 2015). The large disturbances in central fatigue caused by prolonged HIE could have a pronounced effect on cognitive function, thus presenting a further area of investigation.

Within this review, accounting for methodological differences between studies was challenging. For example, 3 studies did not include a rest group or control condition (Brisswalter et al., 1997, Labelle et al., 2013, Reilly and Smith, 1986) but instead compared HIE to low- and moderate-intensities. Whilst these studies enable a comparison of HIE with that of others, they fail to enable any conclusions to be drawn about HIE compared to a rested state. Furthermore, two studies did not employ counterbalancing of exercise intensities (Guizani et al., 2006b, Lo Bue-Estes et al., 2008). These methodological differences make it difficult to assess if changes in cognitive performance were due to the impact of HIE or because of factors such as learning or time effects. In addition, attention should be given to the control of confounding variables. Within the quality criteria check, only 4 studies were deemed to have adequately controlled for confounding. One study met the partial control criteria whilst 5 studies did not report any measures of control for confounding variables. Cognitive performance in healthy individuals is readily influenced by small changes in day to day living as well as aspects such as prior exercise and nutrition; as such, care should be taken to control and report confounding variables where possible.

2.6 Limitations of the current review

Due to the limited number of studies, specific cognitive tasks could not be assessed separately and instead were assigned to general cognitive task categories. Although this was a reasonable approach to examining the research question, this does reduce specificity of results, which may have led to differences within each category being overlooked.

Another important limitation of this review is the methodology applied regarding exercise intensity. This review followed that of others and classified the physical intensity of exercise based on W_{max}, $\dot{V}O_{2max}$ or HR_{max}. Studies that used other values of intensity such as HRR or RPE were compared to the studies that provided data on W_{max} $\dot{V}O_{2max}$ or HR_{max} and eligibility was accordingly determined. Although this limitation was relevant to only three studies that met the eligibility criteria, this strategy undoubtedly contains subjectivity as previously acknowledged (McMorris and Hale, 2012, Schapschroer et al., 2016).

The strategy to classify populations within studies as 'trained' was also partially reliant on subjectivity. The first criteria was an objective measure of participants $\dot{V}O_{2max}$ which was required to meet 'excellent' or 'superior' classification via the ACSM guidelines (Pescatello, 2014). When $\dot{V}O_{2max}$ was not provided however, inclusion was based upon the description of the sample provided by the author(s), which inevitably invites subjectivity. Limiting study inclusion to $\dot{V}O_{2max}$ provision may have excluded studies that clearly included trained participants as demonstrated by their level of sport or hours of training per week and thus it was felt that the criteria applied provided the best opportunity for inclusion of all relevant articles. Whilst everything was done to ensure fitness levels met the required criteria, confidence cannot be guaranteed.

Finally, only articles written in English were included in this systematic review. This criterion is applied within many reviews and has been deemed an acceptable method due to English being the most commonly understood and published language. Nevertheless, articles important to this review may be written in other languages.

2.7 Conclusion & perspectives

In summary, results from this study indicate there to be no significant effects of HIE on measures of simple cognitive processing in individuals with high fitness levels; the effects on complex functions however remain unclear, with evidence suggesting both negligible and detrimental effects. These findings support previous work that have shown differential effects of exercise on various cognitive domains and thus in doing so, emphasise the need to assess multiple cognitive components when conducting exploratory research. This systematic review adds the first to the literature specifically evaluating HIE and cognitive performance, and provides a summary on research within this area to date. Subsequently, this study is applicable to sports and occupations that require the maintenance of cognitive performance whilst under high

physical demands. Amongst other issues discussed within the chapter, this study highlights the need for greater durations of HIE to be assessed alongside the use of cognitive tasks assessing higher-order cognitive processes.

This chapter addressed the first aim of the thesis, to `*Identify and evaluate current understanding concerning the effects of strenuous exercise on cognitive performance*`. Previously there has been no clear consensus on the effects of HIE on cognitive function. It is probable that this is due to the limited pool of studies that have assessed cognitive performance during and following HIE. Furthermore, trained individuals are frequently overlooked when exploring the effects of intensity on cognitive performance; this is surprising considering the populations and situations for application of results. Sporting and military situations provide just a few examples of when trained individuals are required to simultaneously handle high levels of strenuous physical exertion and cognitive loads; thus, it is important that the impact of HIE, particularly on higher-order cognitive processes, is sufficiently examined.

The current review has identified numerous areas that require further investigation that will build upon and add to existing knowledge. As a result, the following chapters in this thesis will explore the effect of different strenuous exercise paradigms on cognitive performance in trained populations.

Chapter 3: The effect of prolonged strenuous exercise on cognitive function, mood, energy and fatigue states in trained cyclists

3.1 Introduction

The well-known physiological effects of exercise have led to several reviews and meta-analyses exploring the impact these effects may have upon cognitive function (Brisswalter et al., 2002, Chang et al., 2012, Lambourne and Tomporowski, 2010, McMorris and Graydon, 2000, Tomporowski, 2003). Contradictory findings emphasise the complexity of the exercise-cognition interaction and have caused authors to stress the importance of control and specificity within their work (Brisswalter et al., 2002, Browne et al., 2017, Chang et al., 2012). Reviews have highlighted six moderating variables to control in such studies: (i) exercise intensity, (ii) exercise duration, (iii) exercise mode (iv) physical fitness of participants, (v) cognitive domain assessed, and (vi) timing of cognitive task administration (Brisswalter et al., 2002, Browne et al., 2017, Chang et al., 2012, Lambourne and Tomporowski, 2010). Generally, improvements are found in cognitive function following moderate-intensity exercise lasting between 20-minutes and 1-hour (Brisswalter et al., 2002, Chang et al., 2012). This improvement has previously been attributed to increases in catecholamine and arousal levels, leading to an optimal level that facilitates cognitive function (Brisswalter et al., 2002, Chang et al., 2012, McMorris et al., 2009). However, when exercise duration lasts more than an hour, and when the intensity of exercise increases, detrimental effects on cognition are reported (Fery et al., 1997, Grego et al., 2004, Labelle et al., 2013, Labelle et al., 2014, Mekari et al., 2015, Tomporowski, 2003). This is proposed to be due to further increases in arousal and catecholamines which causes neural noise and impairs cognitive performance (McMorris, 2016).

The experimental and theoretical literature exploring the effects of strenuous exercise on cognitive performance converges towards impairment (Ando et al., 2005, Browne et al., 2017, Chmura et al., 1994, Cooper, 1973, Davey, 1973, McMorris et al., 2009, Tomporowski, 2003, Yerkes and Dodson, 1908). Not all studies however have observed this effect (Alves et al., 2014, Davranche et al., 2015, Lemmink and Visscher, 2005, Schmit et al., 2015, Tsukamoto et al., 2016a, Winter et al., 2007). In a recent study, Alves et al. (2014) reported improvements in a central executive task following short-duration, high-intensity interval exercise, leading the authors to suggest that exercise intensity itself may not exert a major role in exercise-induced cognitive modulation, but rather the level of induced fatigue may play a more important role. In line with this, Tomporowski (2003) suggested that HIE-induced cognitive impairment may be due to increases in mental fatigue. Thus, assessing both

physical and mental fatigue may provide greater insight into the reasoning behind potential changes in cognitive function.

Increases in metabolic load through greater durations and intensities of exercise are associated with the manifestation of physical fatigue, which is understood to be due to both peripheral (e.g. reduced muscle excitability) and central (e.g. reduction in neural drive) mechanisms (Grego et al., 2005). The appearance of fatigue is known to cause reductions in performance, even in well-trained athletes (Lepers et al., 2000). Prolonged and strenuous intermittent exercise, for example, has been shown to cause metabolic and mechanical perturbations in physical performance (Bell et al., 2014); however, little is known about the effects of such exercise on cognitive function and mood. Studies examining the effect of exercise on cognition have often focussed upon continuous exercise models (Grego et al., 2005, Hogervorst et al., 1996, Labelle et al., 2014, McMorris et al., 2009). This is surprising considering that in many sports and occupations (e.g. military, firefighting), exertion is often intermittent and comprised of both metabolic and mechanical stressors.

In accordance with the effects of exercise on cognition, mood improvements and positive effects of well-being are commonly observed following moderate-intensity exercise (Scully et al., 1998), but not following a single session of intense exercise (Berger et al., 1997), even in trained individuals (Berger and Motl, 2000). Moreover, strenuous exercise can cause worsened mood states compared to pre-exercise (Steptoe and Bolton, 1988). In association with mood, emerging evidence suggests that the maintenance of prolonged exercise requires mental effort, which is necessary to inhibit peripheral and central afferents that arise with physical fatigue (Radel et al., 2017). Based on this, it may be postulated that exercise causes reductions in mental energy and increases in mental fatigue as the brain attempts to modulate activity to maintain physical effort. Thus, the assessment of both cognitive and psychological markers may provide greater insight into any observed effect that sustained exercise may have on central processes.

The systematic review presented in Chapter 2 highlights limited research investigating cognitive function in trained subjects. Analysis of the studies available indicated that strenuous exercise causes an impairment in tasks requiring higher-order cognitive processes whilst having little effect on simple cognitive tasks. In addition to this, the review found that the average exercise duration of all the studies meeting the criteria of ‘’trained’ and ‘high-intensity’ exercise was 5.6 minutes, with the largest duration of exercise lasting approximately 10-minutes and that most of these

studies assessed SRT and CRT, whilst limited studies investigated higher-order cognitive processes such as executive function. To address this gap in the literature and build upon existing knowledge, the first experimental study of this thesis aims to examine the effect of prolonged strenuous exercise on cognitive tasks assessing both simple and complex cognitive performance and mood disturbance, in trained individuals. It was hypothesised that sustained physical exercise requiring high physiological effort, would cause a reduction in cognitive performance requiring higher-order processes despite the trained status of participants. Secondly, it was hypothesised that prolonged exercise would have a negative effect on both mood and measures of physical and mental energy and fatigue.

3.2 Methods

3.2.1 Participants

Statistical power was calculated using commercially available software (G*Power v3.1.9, Düsseldorf, Germany) to determine an adequate sample size for this investigation. Based off of previous studies that examined the effect of acute exercise on executive function (Davranche and McMorris, 2009, Pontifex et al., 2009a), it was estimated that a sample size of 13 would be required to detect significant changes with a two tailed α level of 0.05 and a sufficient statistical power of 0.80 (Cohen, 1992). This returned a hypothesised effect size of 0.8 (Cohen's d - large) for a within subject's design. Consequently, 13 male endurance-trained cyclists that met the inclusion criteria outlined below (see Table 3.1 for participant characteristics) were recruited to participate in the study that took place outside of the racing season.

Participants were provided with a verbal and written explanation of the study prior to providing written informed consent (appendix A) and completed a questionnaire to assess for eligibility and contraindications. Eligibility criteria stated that cyclists must be male, between the ages of 18 and 35 and have been regularly competing (at least a Category 3 British Cycling licence holder or an estimated 16.1 km TT of ≤23 minutes). This was assessed through the completion of health screening (appendix B) and training history questionnaires (appendix C). All cyclists were healthy, had no severe head injuries in the past 12 months and did not take any medication that may have interfered with cognitive function. This study was conducted in accordance with the Helsinki Declaration (1964) and was approved by Northumbria University's Faculty of Health and Life Sciences Ethics committee. All study procedures were

conducted in a laboratory accredited by the British Association of Sport and Exercise Sciences.

Table 3.1 Participant characteristics (mean ± SD)

Variables	
Age (years)	26 ± 5
Body mass (kg)	73.9 ± 11.1
Height (cm)	178.9 ± 8.2
Heart rate maximum (beats·min−1)	191 ± 10
$\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1})	62.1 ± 5.6
W_{max} (W)	415 ± 62

3.2.2 Experimental protocol

Each participant was required to visit the laboratory on three separate occasions. The first visit was used to collect demographic information, determine maximal oxygen uptake ($\dot{V}O_{2max}$; protocol described in Eddens et al. 2017) and familiarise participants with the cognitive performance tasks and psychological measures. During this visit, each participant completed the cognitive and psychological assessments three times to minimise the possibility of learning effects. The present study was part of a larger study which imposed limitations on the current study design. The study was conducted in a repeated measures design; however, it is important to explain that the conditions were not counterbalanced. Each participant completed the exercise condition first. The limitations imposed by this are acknowledged in the limitations section of this chapter (see section 3.5).

The second and third visits comprised of cognitive measures prior to and immediately following either a prolonged strenuous exercise protocol lasting 140 minutes, or seated rest for the same duration (Figure 3.1). During the seated rest, participants were free to relax whilst being instructed not to do anything mentally demanding. To minimise diurnal variation and control for potential influencing variables, participants visited the lab at the same time of day and were asked to refrain from exercise, alcohol and caffeine 24-hours prior to each laboratory visit. Participants were also asked to log all food consumed in a provided food diary 24 hours prior to the first experimental visit and then to replicate this prior to the second experimental visit. During the study period participants were encouraged to consume a carbohydrate-rich diet and to

remain euhydrated. Compliance was assessed via subjective report on each day of testing.

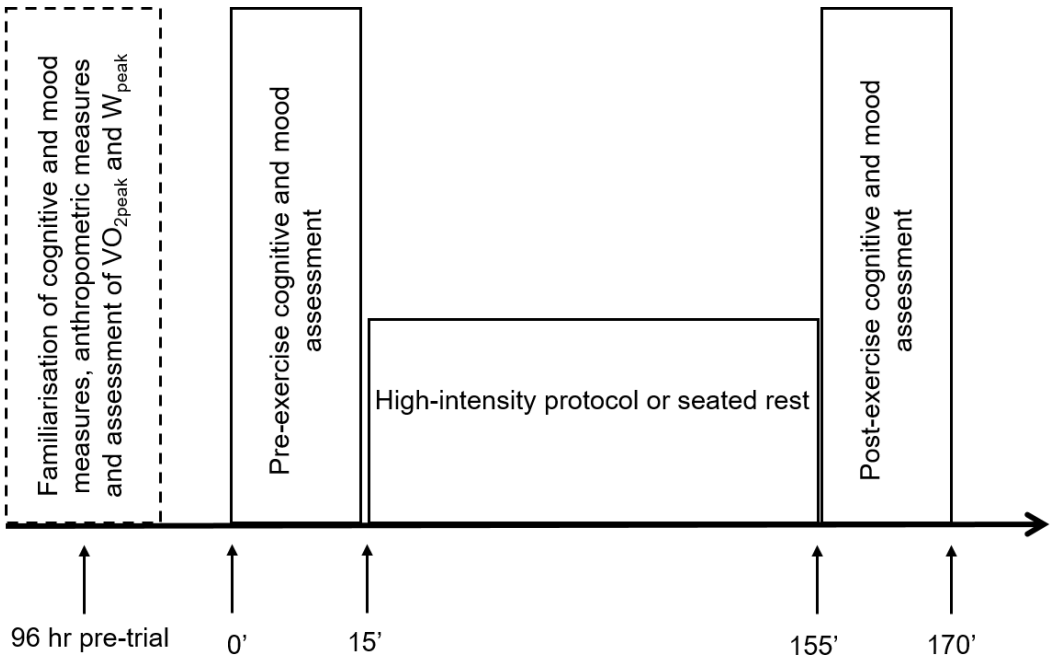

Figure 3.1 Schematic of testing protocol

3.2.3 Cognitive performance measures

Cognitive measures were administered using the Computerised Mental Performance Assessment System (COMPASS, Northumbria University, UK), a programme used to present computerised standard psychometric tests. COMPASS has previously been demonstrated to be sensitive to both exercise and nutritional interventions (Ali et al., 2016, Asamoah et al., 2013, Thompson et al., 2014, Veasey et al., 2013). Cognitive tasks were presented via a laptop computer and responses were recorded via a response pad (comprising of a central RT button, Left/Right/Up/Down and Red/Blue/Green/Yellow) or computer mouse, depending on the task.

The entire cognitive battery took approximately 15 minutes to complete. Participants were tested individually in an isolated booth and were required to wear noise minimising headphones in an attempt to reduce visual and auditory distraction. To measure simple and complex cognitive processes, various measures were utilised including a measure of processing speed (SRT), a more complex measure of processing speed (FCRT), visuospatial short term working memory (Corsi blocks) and executive function, namely response inhibition, cognitive flexibility and selective

attention (Stroop task). These measures have been used in similar research and show a sensitivity to exercise interventions (Bandelow et al., 2010, Brisswalter et al., 1997, Davranche and Audiffren, 2004b, Delignières et al., 1994, Furley and Memmert, 2010a, Hogervorst et al., 1996).

3.2.3.1 Simple reaction time (SRT)

An arrow pointing upwards appeared in the centre of the computer screen at irregular intervals (interstimulus (ISI) interval = 1 to 2.5 seconds). Participants were instructed to press the centre button on the response pad as quickly as possible as soon as the arrow appeared. The task was scored for overall RT (ms) to 35 stimuli. Incorrect responses were not recorded.

3.2.3.2 Four-choice reaction time (FCRT)

Four arrows pointing left, right, up and down individually appeared on the computer screen at irregular intervals (ISI = 1 to 3.5) seconds. Participants were instructed to use the index finger of their dominant hand to press the corresponding button on the response pad, as quickly as possible, when an arrow appeared. The task was scored for correct RT (ms) and accuracy of responses (%) to 32 stimuli.

3.2.3.3 Computerised Corsi blocks

Nine blue squares on a black background were displayed on the computer screen. In a random order, some of the blue squares changed to red and back to blue again. Participants were instructed to remember the sequence and once it had finished, use the cursor to click the blocks in the exact sequence in which they were presented. The task was repeated five times at an increasing level of difficulty (addition of 1 block) with the sequence span beginning at 4 and increasing upwards until the participant could no longer correctly recall the sequences. The task was scored for span score, calculated by averaging the level of the longest three correctly completed trials.

3.2.3.4 Stroop task (Stroop, 1935)

Words describing one of four colours (‘RED’, ‘YELLOW’, ‘GREEN’, ‘BLUE’) were presented in different coloured fonts in the centre of the computer screen. Participants

were instructed to press one of four coloured response buttons in order to identify the font colour (e.g. if the word 'YELLOW' was presented in a red font, the correct response would be to respond with the red button). The presented words were either 'congruent' (word and font were the same colour) or 'incongruent' (word and font were different colours) and were presented in a random order. The task was scored for congruent and incongruent correct response RT (ms) and accuracy (%) to 30 stimuli.

3.2.4 Mood assessment

Mood measures were selected based on previous published studies that investigated the impact of exercise on affective responses (Davranche and Audiffren, 2004a, Moore et al., 2012).

3.2.4.1 Bond-Lader mood scale (Bond and Lader, 1974)

A series of 16 visual analogue scales (VAS) were presented to participants assessing mood, to which participants were asked to answer 'how do you feel right now'. Scored from 0-100, each scale was presented on a straight 100 mm horizontal line anchored at either side by opposite adjectives describing a mood (for full scales see appendix D). Participants were instructed to click at a point on the scale that represented the intensity of how they were feeling at that current point in time. From these scales, three composite scores were calculated describing feelings of alertness, calmness and contentedness, with each of the scales showing high internal validity.

3.2.4.2 Mental and Physical Energy and Fatigue

The state components of the Mental and Physical State and Trait Energy and Fatigue Scale (O'Connor 2006) consist of 12 items that measure four energy and fatigue mood states: Physical Energy, Physical Fatigue, Mental Energy and Mental Fatigue. Participants were asked to indicate, "How do you feel right now with regard to your capacity to perform your typical physical activities" for the physical energy and fatigue questions (appendix E). The instructions were identical for the mental energy and fatigue questions except that the focus was changed to "typical mental activities". The scales ranged from 'I feel I have no' to 'strongest feelings of…ever felt' with the adjectives at the end of each scale being energy/ fatigue/ vigour/ exhaustion/ pep/ feelings of being worn. Participants rated the intensity of their current feelings by marking a point on each of the twelve presented 100 mm VAS. Each VAS item was

scored 0-100 in mm from left to right along the horizontal line with 0 representing the lowest possible score and 100 being the highest. Participants total fatigue and energy scores were derived by summing the three items constituting each of the four state scales (O'Connor, 2006) and thus, the scale scores could range from 0 to 300.

3.2.5 Exercise protocol

Participants completed a prolonged, strenuous stochastic cycling protocol (Table 3.2) on a magnetically braked cycle ergometer (Velotron RacerMate, Seattle, WA, USA) which has previously been used to simulate cycling road race demands (Bell et al., 2014, Vaile et al., 2008). Participants completed a 10-minute self-selected warm-up including 3 × 3 second sprints at a perceived intensity of 70 %, 80 % and 90 % of maximum effort respectively. Following the warm-up, participants went straight into the main exercise task, which consisted of 66 maximal effort sprints of 5, 10 or 15 second duration with specific work to rest ratios of 1:6, 1:3 or 1:1. Sprints were divided into 9 sets, with an active recovery period taking place between sprints and sets where intensity was equally maintained at 40 %–50 % W_{max} achieved at $\dot{V}O_{2max}$. Additionally, a further 9-minutes of sustained effort was incorporated into the protocol through the performance of time trials of 2-minute (after sets 3 and 6) and 5-minute (after set 9) duration. Throughout the protocol, participants were encouraged to complete as much work as possible, water was available *ad libitum* and participants were cooled with an electric fan on a standardised setting. The total duration of the cycling trial was 109 minutes.

Following a brief period of standardised dynamic stretching, participants performed 100 drop-jumps which were separated into five sets of 20 drop-jumps. Participants were given a 10-second rest between each jump and a 120-second rest between each set. Jumps were performed from a height of 0.63 cm and participants were encouraged to jump vertically with maximal force immediately upon landing. Strong verbal encouragement was provided throughout the duration of the protocol. The protocol used has previously been shown to cause significant metabolic and mechanical damage resulting in reductions in performance (Bell et al., 2014, Miyama and Nosaka, 2004).

Table 3.2 High-intensity simulated road cycling race protocol (Vaile et al., 2008). Work – Maximal effort sprint. Active recovery – 40 %-50 % maximum aerobic power (W_{max}). TT (time trial) – Sustained maximal effort.

10-minute warm up at a self-selected pace		
Set number	**Sprint frequency x Duration**	**Work : Rest ratio**
1	12 x 5 s	1 : 6
2	12 x 5 s	1 : 3
3	12 x 5 s	1 : 1
4 min active recovery - *2 min TT* - 4 min active recovery		
4	6 x 10 s	1 : 6
5	6 x 10 s	1 : 3
6	6 x 10 s	1 : 1
4 min active recovery - *2 min TT* - 4 min active recovery		
7	4 x 15 s	1 : 6
8	4 x 15 s	1 : 3
9	4 x 15 s	1 : 1
5 min active recovery - *5 min TT* - 5 min active recovery		

3.2.6 Statistical analysis

All data were analysed using IBM SPSS 22 for Windows (New York, USA). Prior to analysis, outliers were identified as greater or less than 2.5 times the SD of the mean and removed; the relevant *n* for each task is shown in Table 3.3. Sphericity was verified by Mauchly's test; if sphericity was violated, the degrees of freedom were corrected using Greenhouse-Geisser procedure. Baseline values for the exercise and control conditions were statistically compared at baseline using a paired samples t-test. Cognitive performance and psychological measures were analysed using a two-way repeated measures analysis of variance (ANOVA) with condition (exercise, rest) and time (pre, post) as within subject's factors. Significant interaction effects were followed up with prior planned pairwise comparisons with LSD to identify significant differences between individual means. Statistical significance was set at an α level of 0.05.

3.3 Results

All cognitive data can be seen in Table 3.3. Only significant results are reported below.

3.3.1 Baseline measures

There were no significant differences at baseline on any measures with the exception of mental energy (exercise, 200.2 vs control, 223.7; p=0.014). Despite a baseline difference between the conditions, mental energy remained stable in the control condition (p=0.16).

3.3.2 Cognitive performance

A significant interaction effect ($F_{(1,12)}$=5.35, p=0.041, η_p^2=0.33) was observed for RT in the congruent condition of the Stroop task (Figure 3.2). Pairwise comparisons revealed Stroop task congruent RT to be significantly slower post-exercise when compared to pre-exercise (p=0.001). No difference was observed in the control condition (p>0.05). No further differences in cognitive performance were found between or within conditions.

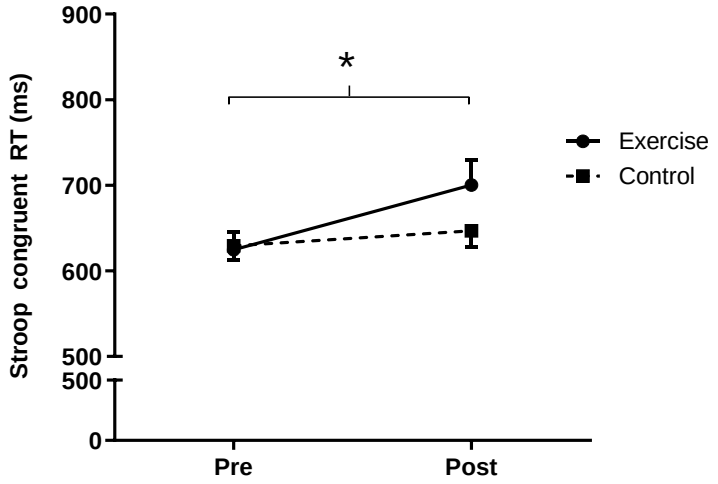

Figure 3.2 Stroop task congruent RT pre- and post-exercise. Data presented as mean ± SEM. *Significant difference pre-post in exercise condition only (p<0.05)

Table 3.3 Cognitive performance results prior to and following each condition

Measure	*n*	Exercise		Control		*p* value		
		Pre	Post	Pre	Post	Condition	Time	X
SRT (ms)	13	321.4 ± 36.7	315.8 ± 33.4	317.0 ± 24.5	325.4 ± 26.2	0.70	0.08	0.22
FCRT correct RT (ms)	13	514.6 ± 64.2	511.2 ± 62.8	486.7 ± 42.0	497.0 ± 41.7	0.09	0.67	0.44
FCRT accuracy (%)	13	99.0 ± 2.0	98.8 ± 2.7	99.3 ± 1.9	99.3 ± 1.8	0.60	0.75	0.67
Corsi blocks (Span Score)	13	6.8 ± 1.3	6.8 ± 1.3	7.0 ± 1.3	7.1 ± 1.2	0.43	0.69	0.69
Stroop correct RT (ms)	13	673.3 ± 67.8	733.1 ± 80.0	667.3 ± 67.0	669.0 ± 74.5	0.09	0.11	0.09*
Stroop task accuracy (%)	12	98.1 ± 2.5	98.5 ± 2.1	97.8 ± 1.8	98.7 ± 1.2	0.99	0.23	0.49
Stroop congruent correct RT (ms)	12	624.6 ± 70.3	700.4 ± 99.5*	629.4 ± 58.5	646.8 ± 65.3	0.33	0.01	0.04*
Stroop congruent accuracy (%)	12	97.6 ± 3.8	96.8 ± 4.8	96.9 ± 4.2	99.1 ± 2.0	0.49	0.51	0.22
Stroop incongruent correct RT (ms)	12	695.2 ± 73.9	747.9 ± 79.8	683.9 ± 82.1	684.4 ± 90.4	0.10	0.22	0.19
Stroop incongruent accuracy (%)	12	97.9 ± 3.2	96.8 ± 4.8	98.3 ± 2.5	98.5 ± 2.5	0.40	0.59	0.34

Data reported as mean ± SD. *Significantly different to previous measure ($p<0.005$). X = interaction

3.3.3 Mood, energy and fatigue states

3.3.3.1 Bond-Lader mood scale

Significant interaction effects were observed for both alertness ($F_{(1,12)}$=6.57, p=0.025, η_p^2=0.35) and contentedness ($F_{(1,12)}$=7.02, p=0.021, η_p^2=0.37) (Figure 3.3). Pairwise comparisons revealed alertness and contentedness ratings to be significantly lower post-exercise when compared to pre-exercise (p<0.05) and when compared to the control condition (p<0.05). No changes were observed in the control condition (p>0.05). No differences within or between conditions were observed for calmness (p>0.05).

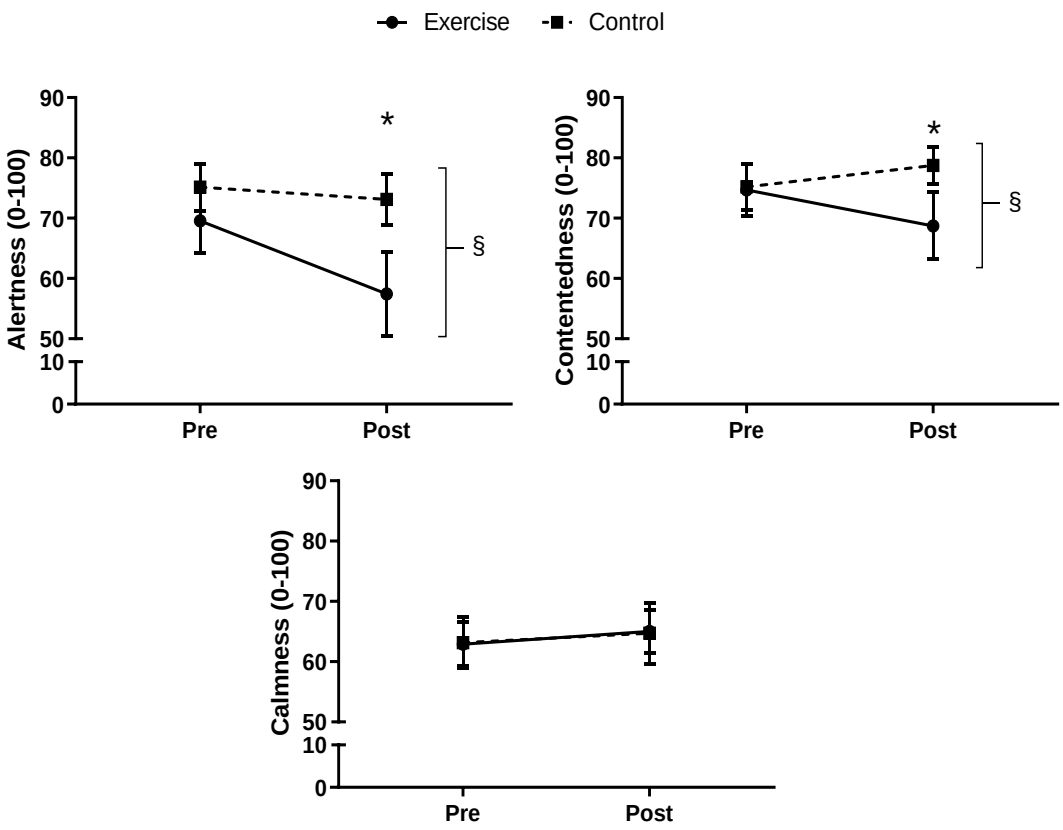

Figure 3.3 Mood subscales of alertness, contentedness and calmness pre- and post-exercise. Data presented as mean ± SEM. §Significant difference between conditions (p<0.05). *Significant difference pre-post exercise (p<0.05)

3.3.3.2 Mental and physical energy and fatigue

Interaction effects for physical energy ($F_{(1,12)}$=20.248, p=0.001, η_p^2=0.63), physical fatigue ($F_{(1,12)}$=24.287, p<0.001, η_p^2=0.67), mental energy ($F_{(1,12)}$=5.591, p=0.036, η_p^2=0.32) and mental fatigue ($F_{(1,12)}$=7.496, p=0.018, η_p^2=0.38) were observed (Figure 3.4). Pairwise comparisons revealed both mental and physical fatigue to be significantly higher and physical and mental energy to be lower, when measured post-exercise compared to pre-exercise (p<0.05) and compared to the control condition (p<0.05).

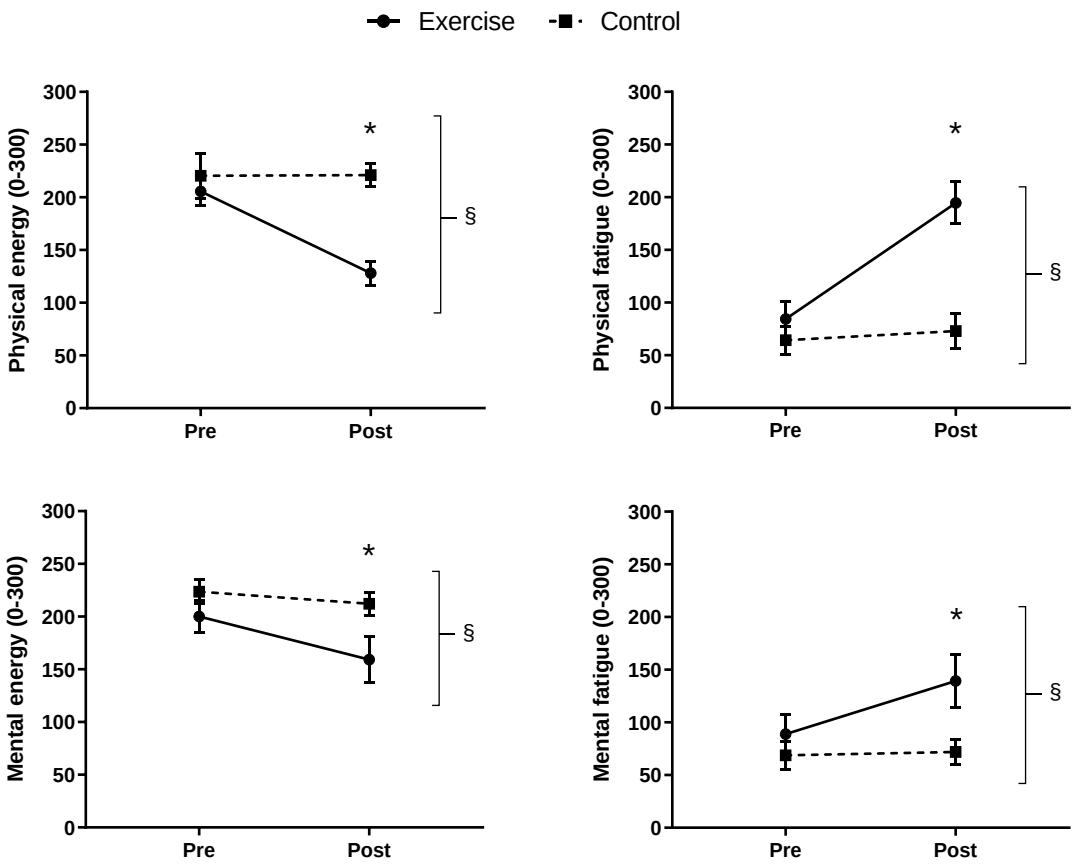

Figure 3.4 Physical and mental energy and fatigue scales pre- and post-exercise. Data presented as mean ± SEM. §Significant difference between conditions (p<0.05). *Significant difference pre-post exercise (p<0.05)

3.4 Discussion

In agreement with our first hypothesis, the main finding of the present study indicated that prolonged, strenuous exercise impaired top-down cognitive processes; with

impairments in Stroop task congruent RT immediately post-exercise while accuracy was maintained. There was no effect however on psychomotor speed or visuospatial memory (VSM) (as assessed by SRT, CRT and the Corsi blocks task respectively). Two components of mood, namely alertness and contentedness, were significantly lower immediately following prolonged strenuous exercise and when compared to the rested control condition. In addition, significant disruptions in mental and physical energy and fatigue states where observed following exercise, with increased levels of fatigue and reduced energy levels.

This is the first study to examine the effects of a prolonged and strenuous mixed-model exercise bout on cognitive function. Many sports and occupational environments involve intermittent periods of high-intensity work that induce both metabolic and mechanical stress (Howatson and Milak, 2009, Nindl et al., 2007). Thus the detrimental effects of this type of exercise on cognitive function may be more representative of the cognitive effects in this field, as opposed to continuous exercise. Classically, poor performance following heavy exercise has been interpreted with regards to high arousal levels (Gould and Krane, 1992). It is proposed that as arousal increases to an optimal level, cognitive facilitation occurs due to the processing of relevant cues. Further increases however, leads to a subsequent narrowing of attention and increased neural noise, particularly on central executive tasks (McMorris, 2016). The results of the current study may therefore be a direct influence of over-arousal. Additionally, the observations of reduced alertness and contentedness alongside increases in physical and mental fatigue, may suggest impaired RT in the current study was also a result of the manifestation of fatigue due to the prolonged and strenuous nature of the exercise bout.

The current findings are, in part, in agreement with those reported by Grego et al. (2005). Within this study, the authors investigated the effect of a prolonged (3-hour) cycling bout on cognitive processes both during and following exercise in a trained cohort of cyclists. Following 2 hours of exercise until the final assessment post-exercise, an increase in the number of errors was reported on a complex map recognition task. Thus, from 120 minutes onwards a decline in accuracy was observed compared to the pre-exercise state. In addition, Grego et al. (2005) also observed reductions in critical flicker fusion following 120-minutes of prolonged exercise, which is suggested to be indicative of CNS fatigue. This is in agreement with studies that have shown central fatigue, as well as peripheral fatigue, manifests following ~2-hours of prolonged exercise (Lepers et al., 2000). As central fatigue is associated with disturbances in perception, coordination and concentration (Lehmann

et al., 1993), its manifestation may have contributed to the reduction in cognitive performance observed in the current study. The finding of a slower RT without a change in accuracy suggests an impairment in the ability to readily respond to the correct information. Interestingly, this finding was only observed in the congruent condition of the Stroop task, indicating that of the executive processes in use, selective attention was affected rather than inhibitory control. The impairment in congruent trials but not incongruent is particularly surprising. The incongruent trials present a more complex condition due to a greater reliance on response inhibition than selective attention and thus, one might expect to see a change in the incongruent condition if a change is observed in the congruent condition, as occurred in McMorris et al. (2009). The remit of the current study cannot provide an explanation for the observed effect, but warrants further investigation with a larger sample size.

Individuals with higher physical fitness levels have been suggested to cope better at high exercise intensities as they have a higher oxygen-carrying capacity, which would confer the ability to compensate for the negative effects of heavy exercise on cognitive task performance (Wang et al., 2013). Furthermore, as physically fitter individuals have a faster rate of recovery following physiological distress (Tomlin and Wenger, 2001), it may be postulated that there is similarly a quicker return to homeostasis at the cognitive level. However, in the current study and that of Grego et al. (2005), reductions in cognitive performance were observed following prolonged strenuous exercise despite the use of trained participants accustomed to cycling. As the exercise protocol utilised induced high physiological stress for over 2-hours, the results may be a consequence of the intense nature of the exercise task and the heavy burden placed on metabolic resource. Accordingly, similar to studies demonstrating differential effects on cognitive performance following shorter exercise bouts in trained and sedentary individuals (Brisswalter et al., 1997, Labelle et al., 2013, Labelle et al., 2014); it could be speculated that the effect of prolonged strenuous exercise on cognitive function may be more severe in untrained individuals that are not accustomed to this intensity and/or type of exercise.

In the current investigation, negative effects on parameters of mood, namely alertness and contentedness, were observed following strenuous exercise. In addition, significant increases in physical and mental fatigue alongside reductions in physical and mental energy were reported. These results are in support of our second hypothesis and existing research which has similarly found detrimental effects of HIE on mood and mental fatigue (Berger and Motl, 2000, Blanchard et al., 2001, Hall et

al., 2002, Rose and Parfitt, 2007, Steptoe and Bolton, 1988). Indeed, increases in mental fatigue alongside reductions in alertness make an individual more vulnerable to the possibility of both mistakes and injury and thus these findings raise important considerations for sporting individuals and military personnel. Interestingly, mood has been found to be related to an individuals preferred intensity (Berger et al., 2016, Saanijoki et al., 2015, Zervas et al., 1993). It has been suggested that this may be reflective of “flow”, described as a pleasurable state of consciousness that can only be achieved when an individual’s competencies are realistically matched against the challenges of the task (Csikszentmihalyi, 2014, Yeung, 1996). The negative mood states observed in the current study following prolonged exercise may therefore reflect the intensity of the task being above the preferred intensity of the trained subjects. In a recent study, Saanijoki et al. (2018) found that high-intensity interval training significantly decreased cerebral μ-opioid receptors binding in the frontolimbic brain regions involved in pain, reward and emotional processing. These effects however, were not observed following moderate-intensity exercise. Decreased binding was correlated with increased negative emotions, thus providing a potential mechanistic pathway for the mediating effect of exercise intensity on mood.

3.5 Practical applications

There are many sporting events that require prolonged cognitive effort for extended durations, with endurance cycling, ultra-endurance, tennis and baseball naming just a few. In all of these sports maintaining attention and reacting quickly is important to success. In endurance cycling for example, when a break from the peloton occurs a cyclist needs to see the attack, judge the importance of the break, decide if they need to break with the attacking cyclist(s) and judge their capacities against the remaining distance to form a decision, all within milliseconds. The findings of this study, which show detrimental effects of prolonged exercise on attentional capacities in trained sporting individuals, highlights the need for the utilisation of cognitive strategies both in training and competition. Furthermore, the reductions in alertness, contentedness, and energy observed alongside increases in mental fatigue highlight probable contributing factors to the observed reduction in selective attention and thus emphasise the importance of adequate nutrition strategies during competition.

3.6 Limitations

A limitation of the present study was the order of testing. Due to being part of a larger study, limitations were imposed and it was not possible to counterbalance conditions. The purpose of counterbalancing is to control for order effects and minimise confounding variables. In the current study, all subjects participated in the exercise condition first followed by the control condition. To reduce the learning effect, all participants completed three familiarisation trials prior to the first experimental visit. To determine if the study was influenced by an order effect, a two-way (cognitive task x time) repeated measures ANOVA was conducted on familiarisation trials to see if a plateau in learning was reached. Initial analysis revealed significant differences between time points in Stroop congruent correct RT and Stroop incongruent correct RT ($p<0.05$). Pairwise comparisons revealed that in the Stroop congruent correct RT condition there was only a difference between the first and third trial and in the Stroop incongruent correct RT condition there was a significant difference between the first and second familiarisation trial but not between the second and third ($p>0.05$). These results demonstrate that a plateau in learning was reached, therefore reducing the likelihood that there was an order effect in the study. Though the assessment of the familiarisation trials provides greater confidence that the study results were not influenced by an order effect, it is acknowledged that counterbalancing the order of the conditions would have improved the design and is therefore implemented in the subsequent studies of this thesis.

3.7 Conclusion & perspectives

In summary, and in support of the first hypothesis, the main finding of this study is that prolonged strenuous exercise had detrimental effects on selective domains of cognitive function. Specifically, negative effects were observed in the Stroop task, which requires higher-order thinking and more conscious effort than simpler tasks. Despite the trained and competitive status of participants, negative effects were also observed in mood and perceptions of physical and mental energy and fatigue. These findings suggest the need for greater research into cognitive strategies for sports that require extended cognitive effort for prolonged durations. This study is in agreement with the findings in Chapter 2 and adds to the growing body of literature showing differential effects of strenuous exercise on various cognitive domains in addition to detrimental effects of exercise of a prolonged duration.

This chapter addressed the second aim of this thesis, to `*examine the effect of prolonged, strenuous exercise on cognitive performance, mood, energy and fatigue*`. The current study presents novel data illustrating a negative effect of prolonged and strenuous exercise on cognitive performance and mood. This has important implications for endurance sports and military personnel that engage in prolonged durations of high physical exertion. It is appreciated that the current protocol used may not represent the intermittent nature of many sports and occupations and thus, Chapter 4 will expand on the current results and explore the effect of intermittent HIE on cognitive performance and mood. In modern day sporting paradigms, the effect of congested tournament fixtures is becoming of increasing interest and concern, though this remains an unexplored area within the cognition space. Thus, the subsequent chapter will specifically explore the effect of repeated exercise over multiple days on cognitive performance and mood.

Chapter 4: The effect of congested strenuous exercise bouts on cognitive function, mood, energy and fatigue states in trained intermittent sports players

4.1 Introduction

Successful sporting performance is dependent on the ability of an athlete to produce and sustain high levels of physical, technical, cognitive and psychological skills throughout a competition (Knicker et al., 2011). These skills often decline during the final stages of a match or game (McMorris et al., 2015, Royal et al., 2006), with deterioration being attributed to exercise-induced fatigue (Smith et al., 2016b, Rampinini et al., 2009). Residual fatigue accumulated over successive matches can also adversely affect team-sport performance (Ronglan et al., 2006) and has been associated with rises in injury rates (Carling et al., 2016) and reductions in player well-being (Gescheit et al., 2015). Despite the need for sufficient recovery after a match, team-sports players are often required to compete and train within intensified competition periods held over consecutive days, multiple times per week (Ronglan et al., 2006). Rugby 7s epitomises congested fixtures, with most competitions consisting of multiple fixtures across a two-day tournament. These excessive volumes of training and competition put the musculoskeletal, nervous, immune and metabolic systems under high loads which have detrimental effects on subsequent exercise performance (Gescheit et al., 2015). Although the physiological effects of a high-intensity exercise (HIE) bout are well-documented, less is known about the effect of cumulative HIE bouts on cognitive performance, though as shown in Chapter 3 and by Grego and colleagues (2004, 2005), long duration exercise has negative effects. Based on the detrimental physiological and performance observations, it is likely that cumulative residual fatigue and limited recovery between successive performances may compromise fundamental cognitive processes and associated sporting performance.

Individuals who engage in strenuous exercise often report a reduced ability to think, make logical judgements and decisions, and have a reduced mood state. Though not all empirical evidence supports these observations (Davranche et al., 2015, Schmit et al., 2015), the experimental and theoretical literature on the cognitive effect of strenuous exercise converges towards an impairment of cognitive performance (Ando et al., 2005, Browne et al., 2017, Chmura et al., 1994, Cooper, 1973, Davey, 1973, Tomporowski, 2003). It is known that intermittent exercise, such as that performed in team sports, increases both mental (Smith et al., 2016b) and physical (Rampinini et al., 2009) fatigue, which can have detrimental effects on cognitive and sport-specific performance (Casanova et al., 2013, Smith et al., 2016b, Stone and Oliver, 2009).

Many moderating variables influence the exercise-cognition interaction, which highlights the complexity of this construct. Alongside the intensity of exercise,

individual characteristics such as physical fitness and skill level have been demonstrated to have a moderating effect (Chang et al., 2012, Voss et al., 2009). Furthermore, the use of imaging tools has provided robust evidence that long-term exercise training and fitness enhances brain structure and functioning throughout the lifespan (Voss et al., 2011); subsequently the failure to control for physical fitness has been highlighted as a major flaw in previous studies (Brisswalter et al., 2002). It has been suggested that fit individuals with a history of training who are accustomed to strenuous exercise may compensate for the negative effects of fatigue on cognitive function (Tomporowski and Ellis, 1986, Wang et al., 2013), with more favourable cognitive responses reported following intense exercise in trained vs untrained individuals (Delignières et al., 1994). Together with the “cognitive component skills” theory (Mann et al., 2007, Voss et al., 2009), which highlights that athletes show enhanced cognitive performance in perceptual-cognitive measures outside of the sport context, it could be suggested that trained athletic individuals are more resistant to the negative effects associated with intense exercise and cognitive performance.

Within the acute exercise-cognition literature, there appears to be a propensity for studies to assess cognition using exercise paradigms that are not matched to the specific sport of interest (Schapschröer et al., 2016). For instance, cycling protocols have been used to assess the impact of exercise on general and soccer-specific cognitive tasks in soccer players (McMorris and Graydon, 1997b). The importance of assessing athletes’ cognition under congruent sport-specific contexts is highlighted by the observation that different exercise modalities, such as cycling and running, elicit different effects on cognitive function (Lambourne and Tomporowski, 2010) and familiarity with exercise modality influences brain cortical activity (Brümmer et al., 2011). It is suggested that differences in the metabolic cost of each exercise mode may alter the attentional demands required and thus impose different loads on cognitive processes (Scott et al., 2006). Consequently, when exploring the impact of sport on cognitive function it is important that the exercise protocol is representative of the participant’s habitual sport. As such, when assessing the effect on cognitive function of intermittent sports such as soccer and rugby, which are characterised by frequent bouts of high-intensity repeated sprint activity punctuated by short periods of recovery, exercise protocols of a similar nature should be employed (Austin et al., 2013).

Several studies designed to assess the effects of strenuous exercise on cognitive function have focussed specifically on the acute effects either during or immediately post-exercise (Chang et al., 2012). Whilst this sheds light on acute exercise-induced

modulation of cognition, it fails to provide an insight into the impact of cumulative or residual effects of exercise on cognitive function during subsequent sport performance. As the last game within a tournament fixture is often the pinnacle match, it is important to consider the impact of repeated, multi-day exercise bouts on cognitive performance and mood. Thus, in relation to the third aim of this thesis, the purpose of the present study was to investigate the effect of multiple high-intensity intermittent exercise bouts, performed over two consecutive days, on cognitive performance and mood in trained team-sports players that are familiar with the type and mode of exercise imposed. It was hypothesised that cumulative fatigue, as a consequence of multiple exercise bouts, would cause a deterioration in cognitive performance and mood despite the trained status of the participants.

4.2 Methods

4.2.1 Participants

Statistical power was calculated using commercially available software (G*Power v3.1.9, Düsseldorf, Germany) to determine an adequate sample size for this investigation. In the absence of any directly relevant data, analysis was based on a based on a hypothesised effect size of 0.3 (Cohen's d - small) for a within subject's design. It was estimated that a sample size of 20 would be required to detect significant changes with a two tailed α level of 0.05 and a sufficient statistical power of 0.80 (Cohen, 1992). Thus with the inclusion of a 20 % drop-out rate, twenty-four well-trained male rugby players were recruited to participate in the study. Mean ± SD age, height and body mass were 21.4 ± 1.7 years, 88.2 ± 9.0 kg and 181.7 ± 5.2 cm, respectively. Volunteers had at least six years' competitive rugby experience, and were currently playing within the top five divisions in the English Rugby Union system. This was assessed through the completion of a training history questionnaire. Participants had not experienced concussion in the preceding 3 months and were not taking any medications that might interfere with cognitive function. The study was conducted in accordance to the Declaration of Helsinki (1964) and was approved by the Faculty of Health and Life Science Ethics Committee at Northumbria University, UK.

All participants were informed of the purposes of the study, signed a written informed consent before the study commenced and completed a health screening

questionnaire. All study procedures were conducted in a laboratory accredited by the British Association of Sport and Exercise Sciences.

4.2.2 Study design

The study was structured using a randomized, counter-balanced, crossover design that consisted of five laboratory visits. The first visit was an initial screening that included the collection of demographic information and familiarisation with the cognitive tasks, subjective measures and experimental procedures. During this session, the battery of cognitive tasks was performed three times to minimise learning effects. Following this, four experimental visits were conducted, where each condition (exercise vs. rested control) was carried out over two consecutive days, in a randomised counter-balanced manner, with a minimum of seven days between conditions. In an attempt to simulate a two-day congested competition period, during each visit, participants completed the cognitive tasks six times; pre and post each of three exercise/control sessions with a three-hour rest in between each bout. Testing was conducted at the same time of day on each occasion. On each experimental day, after each exercise or control session, standardised food was provided. To standardise food consumption in the morning and evenings prior to visits, participants were provided with a food diary and asked to mimic food consumption. Participants were required to refrain from alcohol consumption, caffeine and exercise 24-hours prior to the start of each trial and were asked to attain a minimum of 7-hours sleep on nights prior to each testing day. Self-reported compliance was checked prior to testing.

4.2.3 Experimental Procedure

Upon arrival each experimental day, participants confirmed that they had not suffered a concussion since their previous visit and had complied with the study requirements. Following this, baseline completion of the cognitive tasks, mood, fatigue and energy scales was undertaken. Participants assigned to complete the exercise condition were fitted with a HR monitor (Polar RS800CX, Polar Electro, Finland) and completed a standardised 15-minute warm-up. This consisted of 5-minutes on a cycle ergometer (Watt bike Pro, Nottingham, UK) maintaining between 150-200 Watts, followed by a series of dynamic stretches and shuttle runs at 60 %, 70 % and 80 % of maximal effort. Timing gates (SmartSpeed, Fusion Sport, Australia) were positioned at 0 and

20 m to record sprint times; participants were instructed to start with their foot approximately 30 cm from the start line to avoid premature triggering of the timing system. After a 5-second count down, participants completed 20 x 20 m sprints with a 20 s active recovery period. Participants were instructed to give maximal-effort for each sprint and stop within a 10 m deceleration zone. Congruent to the habitual sport of the participants, this protocol was adapted from a previous study in rugby players and is in line with global position system (GPS) data in rugby (Austin et al., 2013, Suarez-Arrones et al., 2012). Standardized verbal encouragement was provided throughout. Immediately upon completion of the final sprint, a capillary blood sample, for determination of peak blood lactate concentration, was taken and participants provided their RPE using a 15-point RPE scale (Borg, 1998). Participants were then seated in a quiet testing booth to repeat the cognitive performance tests, mood measures and fatigue and energy scales. A three-hour gap was then provided prior to the next session; during this time period participants were free to relax whilst being instructed not to do anything mentally demanding. The control condition was identical to the exercise condition with the exception that no exercise was undertaken and no blood samples, HR or RPE measures were provided. In place of exercise, subjects remained seated in a quiet area for 20 minutes to mimic the same time required for the exercise protocol (Figure 4.1).

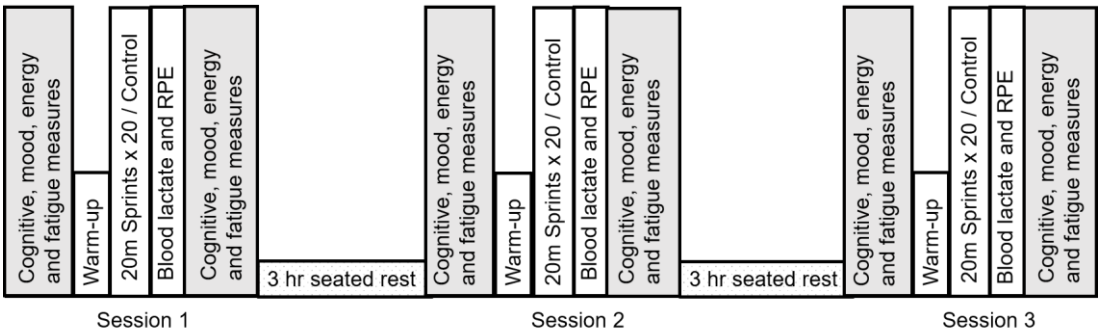

Figure 4.1 Schematic of testing protocol over day 1. This protocol was replicated on day 2.

4.2.4 Cognitive and mood measures

Cognitive measures were administered using COMPASS (Northumbria University, UK). The cognitive battery of tests took approximately 15-minutes to complete and included simple reaction time (SRT), four-choice reaction time (FCRT), Corsi block task and the Stroop task. Mood was assessed via the Bond-Lader mood scale and

via the Mental and Physical State and Trait Energy and Fatigue Scale; for full descriptions of cognitive tasks and scales please refer to the methods section in chapter 3.

4.2.5 Statistical analysis

All data were analysed using statistical software (IBM SPSS 22 for Windows, New York, USA). Prior to analysis, outliers were identified as greater or less than 2.5 times the SD of the mean and removed; the relevant *n* for each task is shown in Table 4.1. Baseline scores between conditions were assessed with a paired samples t-test and are reported in section 4.3.1.1 and 4.3.2.1 for cognitive and mood, energy and fatigue results respectively. To assess the effect of strenuous exercise across consecutive days, as well as pre and post multiple exercise bouts, a four-way (condition x day x session x pre-post) repeated measures ANOVA was conducted on all cognitive performance, mood, energy and fatigue measures. Blood lactate concentration, RPE, sprint time and HR were assessed via a two-way (day x exercise session) ANOVA. A p value of <0.05 was considered significant and pairwise comparisons were used to follow-up on any significant interaction effects revealed by the ANOVAs. Sphericity was assumed if Mauchly's test score returned $p \geq 0.05$; if sphericity was violated, the degrees of freedom were corrected using Greenhouse-Geisser procedure.

4.3 Results

All cognitive data can be seen in Table 4.1. Significant main effects and interactions involving condition are reported below.

4.3.1 Cognitive Performance

4.3.1.1 Baseline differences

Day 1 baseline differences were observed between the control and exercise condition for Stroop correct RT (696.5 vs 661.4; p=0.008) and Stroop incongruent correct RT (715.5 vs 671.5; p=0.011). Following analysis however, these two differences in baseline cognitive function were not related to outcomes significantly affected by the intervention and were therefore not further investigated.

4.3.1.2 Four-choice reaction time

A condition x day interaction effect ($F_{(1,20)}$=6.24, p=0.02, η_p^2=0.21) revealed FCRT to be significantly slower across day 2 in the exercise condition when compared to day 1 (p<0.05) with no such effect in the control condition (Figure 4.2). A three-way condition x session x pre-post interaction ($F_{(2,40)}$=3.41, p=0.04, η_p^2=0.15) found RT following session 3 was slower than following session 2 in the exercise condition (p=0.001), irrespective of day.

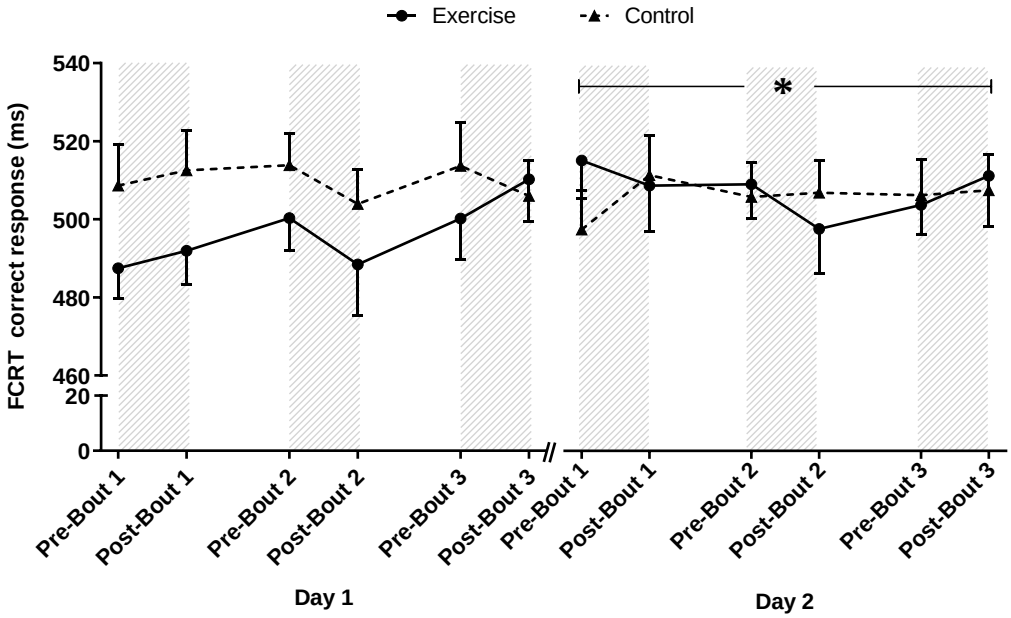

Figure 4.2 Four-choice reaction time pre and post each session of high-intensity exercise/rest over two-consecutive days. Data presented as mean ± SEM. *Significantly different to day 1 (p<0.05)

4.3.1.3 Corsi blocks task

Significant interactions between condition x session ($F_{(2,38)}$=3.56, p=0.038, η_p^2=0.16) and condition x pre/post ($F_{(1,19)}$=10.4, p=0.004, η_p^2=0.35) were observed. Pairwise comparisons following a significant condition x session x pre/post interaction ($F_{(1,19)}$=3.40, p=0.044, η_p^2=0.15) revealed that this was due to a decline in performance post-exercise during session 2 (p=0.001) and 3 (p=0.003) that was not observed in the control condition. Span score was also significantly lower in the exercise condition when compared to control when measured pre and post session 2 and post session 3 (all p<0.05; Figure 4.3).

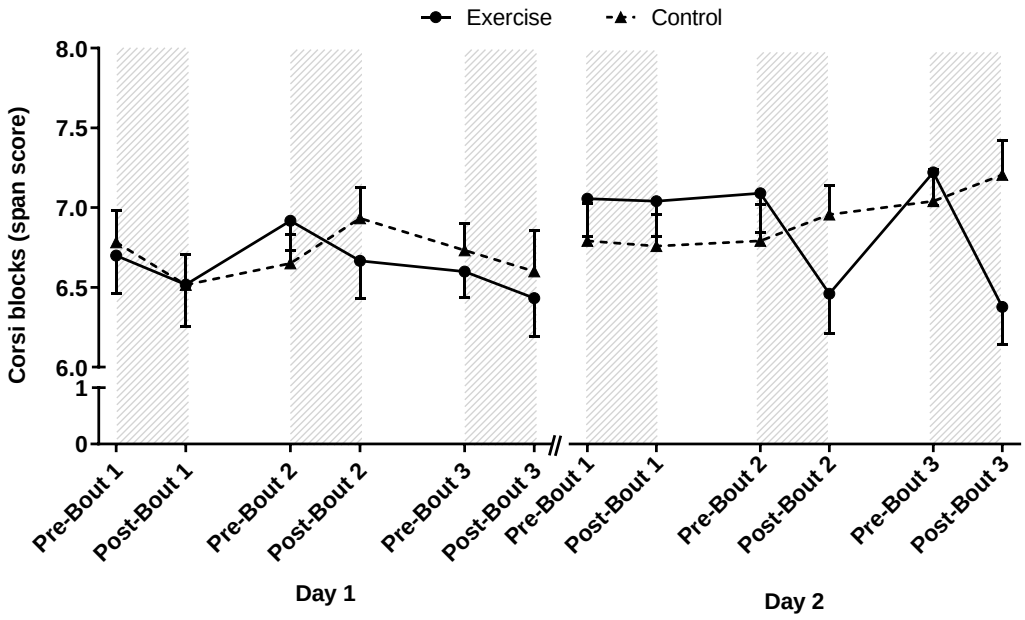

Figure 4.3 Corsi blocks span score pre and post each session of high-intensity exercise/rest over two-consecutive days. Data presented as mean ± SEM. See text 4.3.1.3 for significant differences

4.3.1.4 Stroop test

A condition x pre-post interaction ($F_{(1,18)}$=9.07, p=0.007, η_p^2=0.36) was observed for Stroop congruent correct RT, indicating faster performance post-exercise compared to pre (p=0.001), that was not observed in the control condition. A significant condition x day interaction was observed for overall Stroop accuracy ($F_{(1,18)}$=4.79, p=0.04, η_p^2=0.21), which was driven by an effect on incongruent stimuli ($F_{(1,18)}$=6.77, p=0.02, η_p^2=0.27). In the exercise condition, performance on day 2 was significantly worse than day 1 (p=0.03) and compared to the control (p=0.008; Figure 4.4). A condition x pre-post interaction for Stroop incongruent accuracy ($F_{(1,18)}$=7.66, p=0.01, η_p^2=0.30) revealed a pre-post improvement in the control condition irrespective of day or session (p=0.02), that was not observed exercise condition.

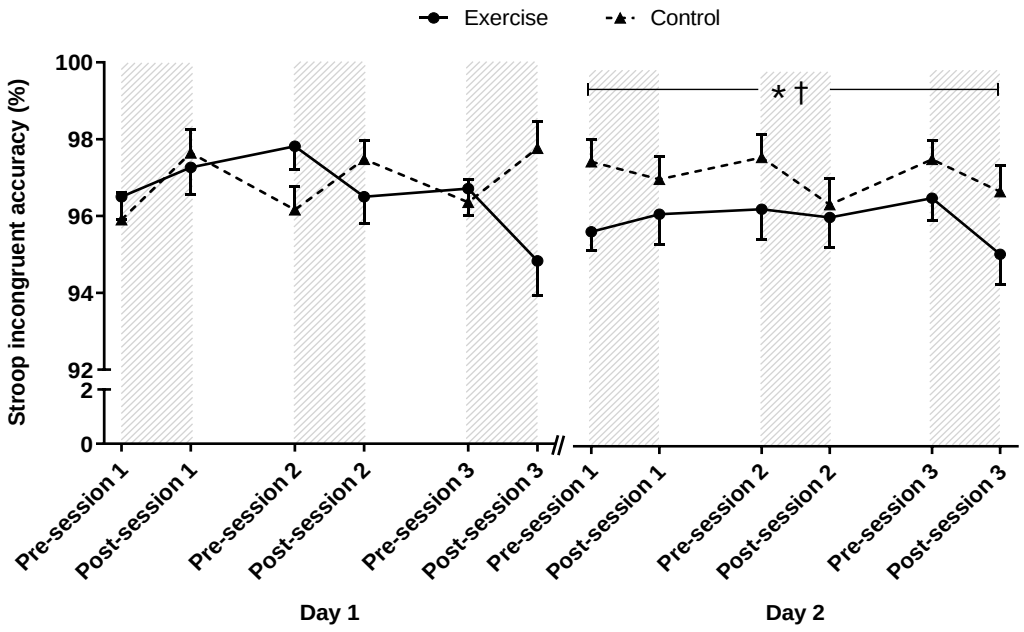

Figure 4.4 Stroop task incongruent accuracy pre and post each session of high-intensity exercise/rest over two-consecutive days. Data presented as mean ± SEM. *Significantly different to day 1 (p<0.05); †significantly different to control condition on day 2

Table 4.1 Raw scores for each cognitive measure across day 1 and day 2 in both the exercise and control condition

Measure	*n*	Condition	Day	Pre-session 1	Post-session 1	Pre-session 2	Post-session 2	Pre-session 3	Post-session 3
Simple reaction time (ms)	23	Exercise	1	319.7 ± 30.2	334.5 ± 32.5	320.4 ± 25.6	341.3 ± 40.4	331.6 ± 30.7	342.5 ± 42.1
			2	325.4 ± 27.0	345.8 ± 33.7	335.2 ± 32.1	338.9 ± 27.8	336.7 ± 29.4	338.5 ± 28.9
		Control	1	319.7 ± 20.9	331.7 ± 27.7	331.8 ± 33.9	332.3 ± 24.2	336.8 ± 34.9	332.8 ± 29.9
			2	324.4 ± 28.2	333.4 ± 34.9	321.7 ± 21.0	339.3 ± 34.4	333.5 ± 33.3	333.6 ± 46.5
Four-choice reaction time accuracy (%)	21	Exercise	1	99.4 ± 2.1	99.4 ± 1.3	99.6 ± 1.5	99.6 ± 1.1	99.4 ± 1.3	99.4 ± 1.6
			2	99.3 ± 1.7	99.7 ± 0.9	99.3 ± 2.2	99.0 ± 1.8	99.0 ± 2.1	98.7 ± 2.7
		Control	1	99.1 ± 1.8	99.9 ± 0.7	99.7 ± 0.9	99.1 ± 2.0	99.6 ± 1.1	100.0 ± 0.0
			2	99.3 ± 1.4	99.9 ± 0.7	98.8 ± 2.7	99.3 ± 1.7	99.4 ± 1.3	99.1 ± 1.4
Four-choice correct response RT (ms)	21	Exercise	1	487.5 ± 34.9	491.9 ± 41.1	500.2 ± 42.0	488.4 ± 62.7	500.2 ± 53.2	510.2 ± 52.5
			2*	515.6 ± 50.9	509.1 ± 59.9	509.5 ± 45.1	497.9 ± 59.1	504.1 ± 35.3	511.6 ± 65.3
		Control	1	508.6 ± 53.9	512.5 ± 49.8	513.9 ± 40.9	503.9 ± 45.8	513.7 ± 57.4	506.0 ± 40.9
			2	497.8 ± 40.7	511.8 ± 51.1	506.2 ± 43.9	507.3 ± 39.7	506.6 ± 46.8	507.9 ± 46.1

Table 4.1 Raw scores for each cognitive measure across day 1 and day 2 in both the exercise and control condition (continued)

Measure	*n*	Condition	Day	Pre-session 1	Post-session 1	Pre-session 2	Post-session 2	Pre-session 3	Post-session 3
Corsi blocks (Span Score)	20	Exercise	1	6.7 ± 1.1	6.5 ± 1.2	6.9 ± 0.8	6.7 ± 1.1	6.6 ± 0.7	6.4 ± 1.1
			2	7.1 ± 1.1	7.1 ± 1.0	7.1 ± 1.1	6.5 ± 1.1	7.2 ± 0.9	6.4 ± 1.1
		Control	1	6.8 ± 0.9	6.5 ± 0.8	6.7 ± 0.8	6.9 ± 0.9	6.7 ± 0.8	6.6 ± 1.1
			2	6.8 ± 1.1	6.8 ± 0.9	6.8 ± 1.0	6.9 ± 0.8	7.1 ± 0.9	7.2 ± 0.9
Stroop task accuracy (%)	19	Exercise	1	97.3 ± 2.2	97.6 ± 2.1	97.7 ± 2.1	97.2 ± 3.0	97.0 ± 2.5	95.9 ± 2.9
			2†	96.9 ± 2.0	96.8 ± 2.5	96.8 ± 3.0	96.8 ± 3.1	97.0 ± 2.4	96.1 ± 2.8
		Control	1	96.8 ± 2.3	97.7 ± 2.4	96.8 ± 2.4	97.5 ± 2.0	97.2 ± 2.1	97.7 ± 2.6
			2	98.2 ± 1.8	97.4 ± 2.3	97.5 ± 3.0	97.1 ± 2.2	97.8 ± 2.0	97.4 ± 2.8
Stroop task correct response RT (ms)	19	Exercise	1	661.4 ± 55.1	646.9 ± 64.4	667.9 ± 64.1	635.9 ± 65.4	648.8 ± 58.6	646.2 ± 69.5
			2	651.6 ± 56.5	640.6 ± 47.6	665.4 ± 59.6	653.0 ± 63.4	645.9 ± 62.1	638.4 ± 69.5
		Control	1	696.5 ± 72.7	677.9 ± 53.8	676.5 ± 61.8	673.5 ± 71.8	680.4 ± 80.4	665.3 ± 62.5
			2	650.7 ± 56.8	672.1 ± 58.0	655.6 ± 56.3	654.2 ± 66.4	646.0 ± 61.2	650.5 ± 66.4
Stroop task incongruent accuracy (ms)	19	Exercise	1	96.5 ± 3.0	97.3 ± 3.3	97.8 ± 2.7	96.5 ± 3.6	96.7 ± 3.5	94.8 ± 4.6
			2*†	95.7 ± 2.7	96.2 ± 3.9	96.3 ± 4.0	96.1 ± 4.1	96.6 ± 3.2	95.1 ± 3.9
		Control	1	95.9 ± 3.5	97.6 ± 2.8	96.2 ± 2.4	97.5 ± 2.4	96.4 ± 3.1	97.8 ± 2.6
			2	97.6 ± 2.7	97.1 ± 3.2	97.7 ± 2.9	96.4 ± 3.7	97.6 ± 2.4	96.8 ± 3.6

Table 4.1 Raw scores for each cognitive measure across day 1 and day 2 in both the exercise and control condition (continued)

Measure	*n*	Condition	Day	Pre-session 1	Post-session 1	Pre-session 2	Post-session 2	Pre-session 3	Post-session 3
Stroop task incongruent correct response RT (ms)	19	Exercise	1	671.5 ± 58.5	662.3 ± 72.2	678.8 ± 65.9	649.7 ± 71.4	666.9 ± 66.4	664.1 ± 76.3
			2	662.5 ± 66.4	655.8 ± 51.2	668.1 ± 67.3	663.3 ± 75.7	661.4 ± 71.6	665.4 ± 72.0
		Control	1	715.5 ± 85.2	700.0 ± 64.6	688.7 ± 79.9	688.6 ± 82.1	704.6 ± 97.6	678.6 ± 66.3
			2	669.9 ± 74.4	692.5 ± 64.4	675.6 ± 71.0	668.1 ± 68.8	661.1 ± 65.4	665.4 ± 72.0
Stroop task congruent accuracy (%)	19	Exercise	1	98.8 ± 2.1	98.2 ± 2.5	97.6 ± 2.4	98.6 ± 4.0	97.8 ± 2.5	97.9 ± 4.0
			2	99.4 ± 1.9	97.8 ± 3.5	98.1 ± 3.3	98.0 ± 2.8	97.7 ± 4.2	98.1 ± 3.1
		Control	1	98.5 ± 2.7	97.6 ± 3.6	97.7 ± 3.9	97.9 ± 3.1	98.7 ± 2.2	97.7 ± 4.5
			2	99.2 ± 1.8	97.9 ± 3.5	97.2 ± 6.5	98.1 ± 3.0	98.5 ± 2.7	98.8 ± 2.6
Stroop task congruent correct response RT (ms)	19	Exercise	1	639.8 ± 57.5	615.2 ± 59.1	646.2 ± 73.1	610.0 ± 64.1	620.2 ± 56.3	608.7 ± 70.0
			2	629.2 ± 50.1	611.4 ± 53.3	631.2 ± 63.4	631.5 ± 63.4	610.1 ± 50.0	608.1 ± 82.8
		Control	1	656.6 ± 63.4	631.7 ± 42.7	658.9 ± 54.0	639.4 ± 61.4	634.4 ± 67.1	635.3 ± 77.0
			2	614.0 ± 42.4	632.1 ± 55.1	612.9 ± 36.9	631.9 ± 80.0	613.9 ± 79.3	621.6 ± 66.3

Data presented as mean ± SD. *Significantly different to day 1 ($p<0.05$). †Significantly different to control condition ($p<0.05$).

4.3.2 Mood, energy and fatigue states

A condition main effect was found for all three subscales of the Bond-Lader mood scale, indicating that calmness ($F_{(1,23)}$=18.14, p<0.001, η_p^2=0.44), alertness ($F_{(1,23)}$=5.66, p=0.03, η_p^2=0.20) and contentedness ($F_{(1,23)}$=13.01, p=0.001, η_p^2=0.36) were all lower in the exercise condition than the control.

4.3.2.1 Baseline differences

Baseline differences in the control vs exercise condition were observed for physical energy (176.8 vs 201.8; p=0.006), mental energy (175.4 vs 206.3; p=0.002), alertness (59.7 vs 67.9; p=0.024) and calmness (72.3 vs 60.6; p=0.005). Some of the mood outcomes were affected by exercise and were therefore further explored. Of the interaction effects observed, alertness, physical energy and mental energy were all significantly greater at baseline in the exercise condition. Despite this, all variables decline over day 2 in the exercise bout, while they rise and remain stable in the control condition. Together with the significant increases in both mental and physical fatigue, confidence is given that the results of the aforementioned psychological variables are due to intervention and not the disparity observed at baseline.

4.3.2.2 Alertness

A condition x day interaction effect ($F_{(1,23)}$=18.06, p<0.001, η_p^2=0.44) indicated that alertness was significantly lower on day 2 in the exercise condition compared to day 1 (p=0.001) and the control condition (p<0.001; Figure 4.5). A condition x session interaction effect ($F_{(1,23)}$=6.52, p<0.005, η_p^2=0.22) indicated that alertness significantly increased from session 1 to session 2 in the control condition (p<0.005), whereas in the exercise condition it significantly decreased from session 1 to session 3 (p<0.005) and from session 2 to session 3 (p<0.001).

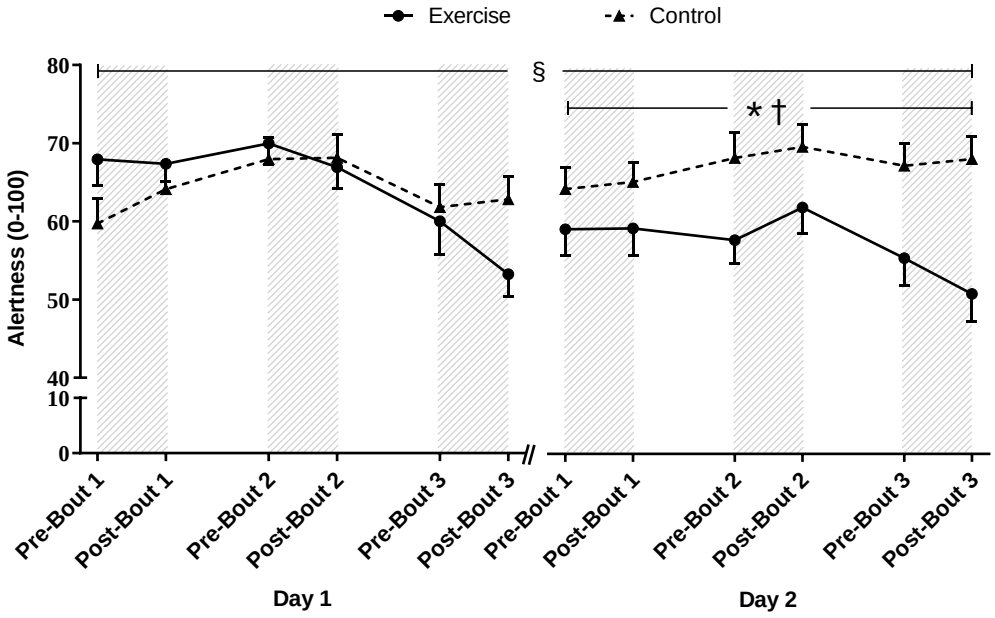

Figure 4.5 Alertness pre and post each session of high-intensity exercise/rest over two-consecutive days. Data presented as mean ± SEM. [§]Condition main effect (p<0.05); *significantly different to day 1 (p=0.001); [†]significantly different to control condition on day 2 (p<0.001)

4.3.2.3 Contentedness

A condition x day interaction effect for contentedness ($F_{(1,23)}$=10.14, p=0.004, η_p^2=0.31) indicating it was significantly lower on day 2 in the exercise condition compared to day 1 (p<0.05) and the control condition (p<0.001; Figure 4.6). A condition x session x pre/post interaction effect was also observed ($F_{(2,46)}$=6.278, p=0.004, η_p^2=0.21). Pairwise comparisons indicated that contentedness increased from pre- session 1 to pre- session 2 in the control condition (p<0.05), whereas in the exercise condition post-session three ratings were significantly lower than post-session 2 (p=0.019), and 1 (p=0.036). Post-exercise contentedness ratings were also significantly lower following session 3 than immediately before (p=0.014), whereas these ratings increased in the control condition (p<0.05). Content ratings were also significantly lower in the exercise condition compared to control pre- and post-session 1, pre-session 2 (all p<0.05) and post-session 3 (p<0.001).

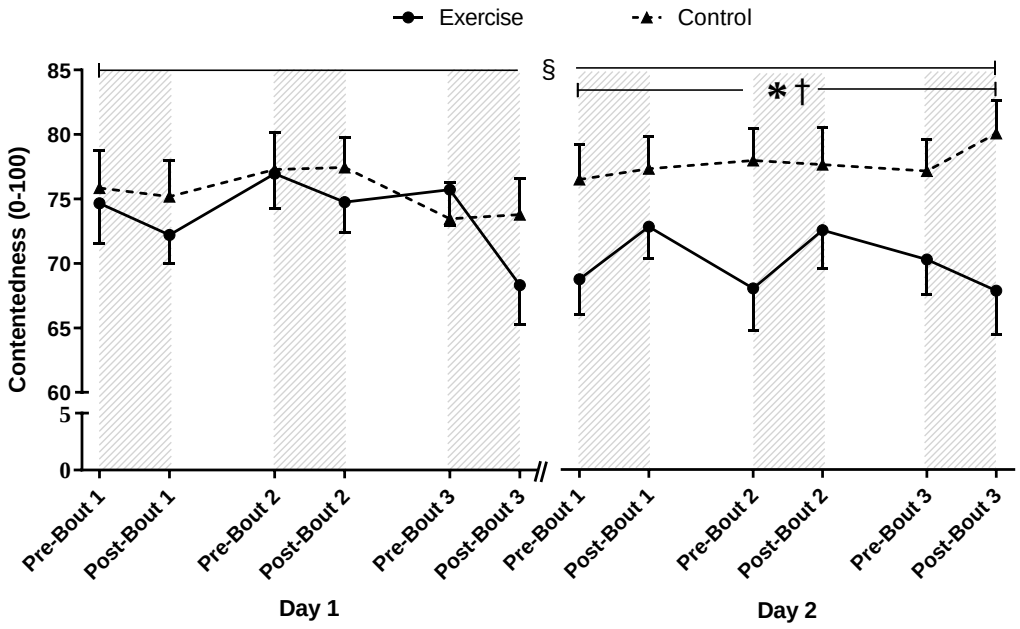

Figure 4.6 Contentedness pre and post each session of high-intensity exercise/rest over two-consecutive days. Data presented as mean ± SEM. §Condition main effect (p=0.001), *significantly different to day 1 (p=0.001); †significantly different to control condition on day 2 (p<0.001)

4.3.2.4 Calmness

A condition x pre-post interaction ($F_{(1,23)}$=6.80, p=0.015, η_p^2=0.23) indicated that post-exercise calmness was significantly lower than pre-exercise (p=0.01) while no change was observed in the control condition (p>0.05; Figure 4.7). A condition x session ($F_{(2,46)}$=5.05, p=0.01, η_p^2=0.18) and a condition x day x session interaction ($F_{(2,46)}$=7.69, p=0.001, η_p^2=0.25) revealed that calmness was higher during session 1 on day 2 compared to day 1 in the exercise condition (p<0.001). Calmness significantly increased from session one to session 2 (p<0.05) and 3 (p<0.001) on day 1 in the exercise condition but decreased from session 1 to session 3 on day 2 (p<0.05) and was lower on all sessions except session three on day 1 in the exercise condition compared to the control (p<0.05).

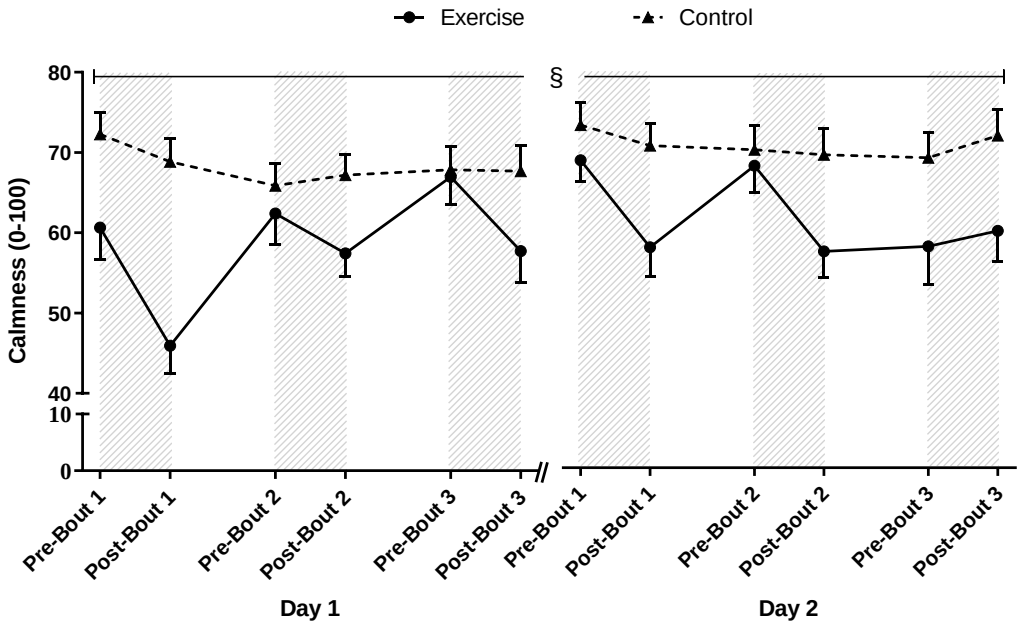

Figure 4.7 Calmness pre and post each session of high-intensity exercise/rest over two-consecutive days. Data presented as mean ± SEM. §Condition main effect (p<0.001)

4.3.2.5 Physical energy

A significant condition main effect ($F_{(1,23)}$=49.15, p<0.001, η_p^2=0.68) and condition x day interaction ($F_{(1,23)}$=22.25, p<0.001, η_p^2=0.49) were observed for physical energy, revealing ratings to be significantly lower in the exercise condition on day 2 compared to day 1 (p=0.001), and compared to the control condition (p<0.001; Figure 4.3). A condition x session interaction indicated lower ratings in session 2 (p=0.048) and 3 (p<0.001) than in session 1 in the exercise condition whilst all sessions were significantly different between conditions (p<0.001), with lower ratings in the exercise condition. A condition x pre-post interaction also revealed lower physical energy post-exercise compared to pre-exercise (p<0.001) and control (p< 0.001).

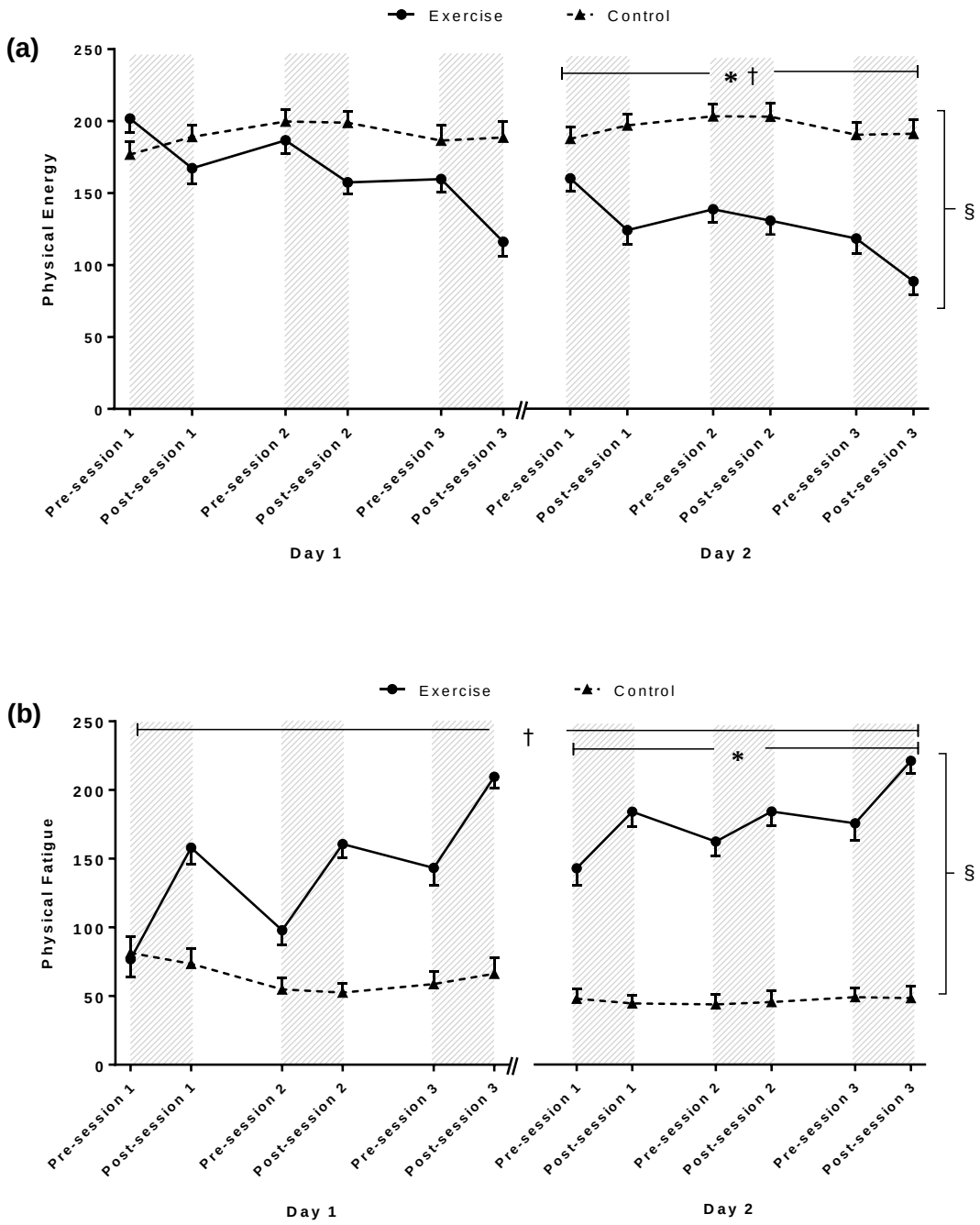

Figure 4.8 (a) Physical energy and (b) physical fatigue pre and post each session of high-intensity exercise/rest over two-consecutive days. Data presented as mean ± SEM. [§]Significant condition main effect (p<0.05). *Significantly different to day 1 (p<0.05). [†]Significantly different to control condition on (a) day 2 (b) both day 1 and 2

4.3.2.6 Physical fatigue

A significant main effect of condition ($F_{(1,23)}$=164.23, p<0.001, η_p^2=0.88) and significant condition x day ($F_{(1,23)}$=43.37, p<0.001, η_p^2=0.88), condition x session ($F_{(2,46)}$=17.38, p<0.001, η_p^2=0.43) and condition x pre/post ($F_{(1,23)}$=36.88, p<0.001, η_p^2=0.62) interactions were observed. Pairwise comparisons following a significant condition x day x session interaction ($F_{(2,46)}$=6.06, p=0.005, η_p^2=0.21) revealed significantly higher physical fatigue during each session on day 2 compared to day 1 (session 1: p=0.001; session 2: p<0.0001; session 3: p=0.014), and between sessions 1 and 3, and 2 and 3 on each day following exercise (all p<0.0001). Conversely, in the control condition, physical fatigue decreased from session 1 to 2 on day 1 (p=0.006) and was significantly lower at session 1 (p=0.002) and session 3 (p=0.033) on day 2 compared to day 1. Physical fatigue was significantly higher when compared to control during each session on each day (all p<0.005). A significant condition x day x pre/post interaction ($F_{(1, 23)}$=9.99, p=0.004 η_p^2=0.30) indicated that ratings were higher pre and post-exercise on day 2 compared to day 1, whereas in the control condition these ratings decreased (all p<0.001). Ratings also increased pre-post exercise on day 1 (p<0.001) and day 2 (p=0.001), with no such effects in the control condition. Ratings in the exercise condition were significantly higher than control pre- and post- on each day (all p<0.001; Figure 4.3).

4.3.2.7 Mental energy

A condition main effect ($F_{(1,23)}$=8.81, p=0.007, η_p^2=0.28), condition x day interaction ($F_{(1,23)}$= 4.74, p=0.001, η_p^2=0.39) and condition x session interaction ($F_{(2,46)}$=6.32, p=0.004, η_p^2= 0.22) revealed mental energy to be lower following exercise on day 2 compared to day 1 (p=0.001; Figure 4.4) and compared to control (p<0.001) while mental energy got lower at each consecutive session compared to the previous session and to the control at session 2 and 3 (p≤0.02). A condition x pre-post interaction ($F_{(1,23)}$=5.79, p=0.025, η_p^2=0.20) indicated that mental energy was lower post-exercise when compared to pre-exercise (p=0.009) and control (p=0.002).

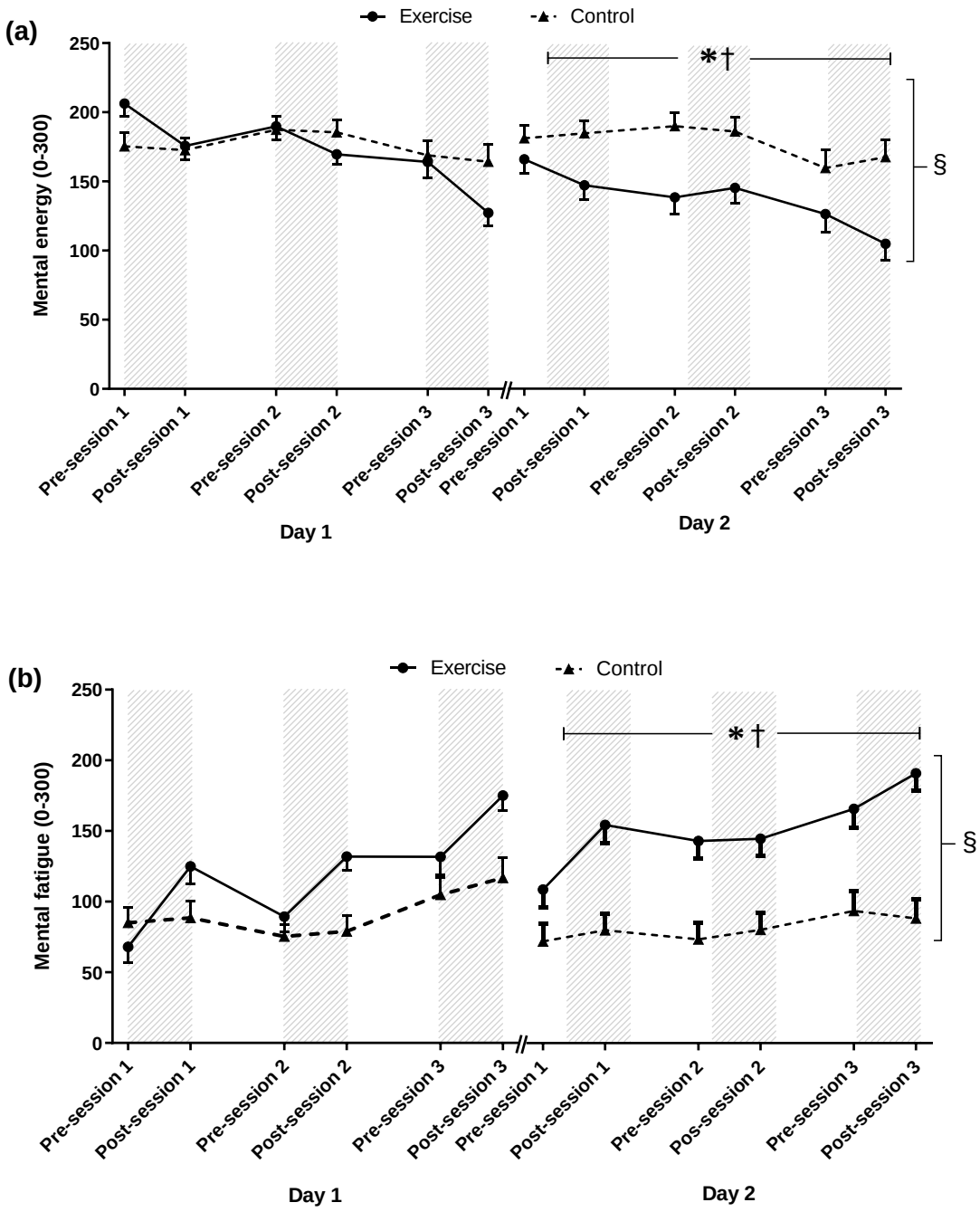

Figure 4.9 (a) Mental energy and (b) mental fatigue pre and post each session of high-intensity exercise/rest over two-consecutive days. Data presented as mean ± SEM. [§]Significant condition main effect (p<0.05). *Significantly different to day 1 (p<0.05). [†]Significantly different to control condition on day 2

4.3.2.8 Mental fatigue

A condition main effect ($F_{(1,23)}$=27.62, p<0.001, η_p^2=0.55) and condition x day interaction ($F_{(1,23)}$=11.16, p=0.003, η_p^2=0.33) revealed mental fatigue to be higher on day 2 compared to day 1 in the exercise condition (p=0.003) while both day 1 and 2 were significantly higher compared to the control (p≤0.02; Figure 4.4). A condition x session interaction ($F_{(2,46)}$=5.99, p=0.005, η_p^2 =0.21) revealed mental fatigue to be increasingly higher at each session (p≤0.02) in the exercise condition whilst also being higher than the control condition (p≤0.003). A condition x pre-post interaction ($F_{(1,23)}$=14.11, p= 0.001, η_p^2=0.38) found post-exercise mental fatigue to be higher than pre-exercise (p<0.001) while the control was lower than the exercise condition at pre (p=0.002) and post (p<0.001).

4.3.3 Performance measures and RPE

Due to technical issues, HR data for 18 of the 24 participants was available for analysis. A session main effect showing an increase in RPE ($F_{(2,46)}$=15.90, p<0.001, η_p^2=0.41) was observed alongside a session main effect for post-exercise blood lactate concentration ($F_{(2,46)}$=15.81, p< 0.001, η_p^2=0.41), which indicated a reduction across each exercise session. In addition, a day main effect for blood lactate ($F_{(1,23)}$=46.601, p<0.001, η_p^2=0.67), sprint time ($F_{(1,23)}$=6.12, p=0.021, η_p^2=0.21) and HR ($F_{(1,17)}$=28.69, p<0.001, η_p^2=0.63) revealed all to be lower on day 2 than day 1 (p<0.05). Performance and RPE data is presented in Table 4.3 below.

Table 4.3 Average: sprint time, HR, RPE and post-exercise blood lactate concentration following each session of repeated sprints on day 1 and 2

	Day	Session 1	Session 2	Session 3
Average sprint time (s) ‡	1	3.43 ± 0.2	3.47 ± 0.1	3.46 ± 0.1
	2	3.51 ± 0.1	3.51 ± 0.1	3.52 ± 0.1
HR_{av} (bpm) ‡	1	178 ± 8	180 ± 6	179 ± 6
	2	175 ± 8	175 ± 8	176 ± 7
BLa (mmol/L) #‡	1	12.4 ± 2.6	11.4 ± 2.5	10.4 ± 2.1
	2	9.9 ± 2.0	9.6 ± 1.8	9.1 ± 1.6
RPE#	1	18 ± 1.1	18.4 ± 1.1	18.7 ± 1.5
	2	18.0 ± 1.9	18.4 ± 1.3	18.8 ± 1.1

HR_{av} = average heart rate; BLa = blood lactate concentration; RPE = rate of perceived exertion. Data presented as mean ± SD. #Significant session main effect (p<0.05). ‡Significant day main effect (p<0.05)

4.4 Discussion

It was hypothesised that cumulative fatigue, as a consequence of multiple exercise bouts, would cause a deterioration in cognitive performance and mood in trained team sports players. In support of the hypothesis, cumulative HIE bouts did result in a deleterious effect on cognitive performance and mood. Specifically, on day 2, both an increase in errors (assessed by response accuracy on the Stroop task) and a slowing of RT (assessed on the FCRT) were observed. In addition, FCRT and VSM (assessed on the Corsi blocks test) were generally worse post-exercise following cumulative exercise bouts. Within the mood measures, both alertness and contentedness were lower following one day of exercise. Furthermore, mental and physical fatigue were significantly higher on day 2 while mental and physical energy were lower.

The results observed in the current study are supported by within-match observations of reductions in technical skill and performance (Rampinini et al., 2009) in addition to reductions in performance across congested matches and tournaments (Ronglan et al., 2006). In contrast to the results of the current study, Tsukamoto and colleagues (2016b) found improved RT on the Stroop task following repeated HIE. Though a positive effect of exercise on Stroop congruent RT was observed in the current study, this was offset by a negative effect on Stroop incongruent accuracy, which also

interacted with day suggesting that the cumulative effect of HIE here was negative. A possible explanation for the contrasting results when compared to those of Tsukamoto and colleagues is that whilst high-intensity was used in their study (90 % $\dot{V}O_{2max}$), the exercise was not at maximal effort and was on a cycle ergometer which has been shown to be a less cognitively demanding activity as compared to running (Lambourne and Tomporowski, 2010). Higham et al. (2012) also observed different findings to the current study. When assessing movement patterns in rugby sevens, the authors found little indication of accumulated fatigue in players when comparing first and last games during tournaments that were held across two-days and consisted of five to six matches. However, this study only reported movement patterns and not skill, perceptual responses or any markers indicative of cognitive performance such as decision-making or missed passes and therefore the true impact of accumulated matches and residual fatigue was not fully assessed. Furthermore, as highlighted by Higham et al. (2012), their results may be representative of effective between-match physiological recovery strategies rather than the effect of exercise-induced fatigue on consecutive performance.

Though the relationship between fundamental cognitive processes and sport-specific cognitive processes is still unclear, it is interesting that the findings of the current study support those of Sinclair and Artis (2013) who found a considerable reduction in sport-specific decision-making and accuracy across a 4-day soccer tournament. Moreover, our results indicating a reduction in accuracy on a higher-order cognitive task (Stroop), supports previous studies that have used intermittent protocols and found reductions in accuracy on both cognitive (Casanova et al., 2013) and performance-specific (McMorris and Rayment, 2007, Stone and Oliver, 2009) tests. This suggests that the effects of cumulative HIE bouts may be specific to more complex tasks and have the potential to impact cognitive processes that form the basis of sporting performance such as decision making, response inhibition and cognitive flexibility.

During HIE hyperventilation blunts increases in cerebral blood flow which can lead to inadequate oxygen, glucose, and lactate delivery to the brain and contribute to the development of central fatigue (Ogoh and Ainslie, 2009). According to Dietrich (2006), studies on cerebral blood flow and metabolism provide the strongest support for the hypofrontality hypothesis that suggests exercise decreases neural activity in the PFC. Based upon this mechanistic theory, it could be postulated that greater resource in the motor cortices was required on day 2 due to the increased fatigue, consequently inhibiting cognitive performance. However, caution must be taken when applying this theoretical model to post-exercise performance as it was designed to specifically

account for the psychological effects during exercise. Given the lack of detailed data about the time it takes for the brain to resume pre-exercise status, there is a lack of confidence when applying this framework to post-exercise changes in cognition.

Previous studies investigating repeated high-intensity interval exercise and executive function have associated reduced lactate levels with reduced executive functioning on the premise that as lactate is a main energy source for the brain during high-intensity activity, lower lactate levels may not adequately support neuronal activity and metabolism (Tsukamoto et al., 2016b). This is thought unlikely in the current study however due to the relatively high lactate levels on day 2 despite the significant decrease from day 1. Indeed, reduced lactate levels suggests reduced glycolysis which is a consequence of fatigue. A recent study by Fiorenza et al. (2019) found multiple short sprints, similar to that in the current study, resulted in neuromuscular fatigue which has been suggested to decrease parasympathetic tone and attenuate executive functioning (Dupuy et al., 2018). Together with the slowing of sprint performance and self-rated increases in physical and mental fatigue, the decline in cognitive and physical performance observed on day 2 of the current protocol may be attributed to both mental (Smith et al., 2016b) and physical (Rampinini et al., 2009) fatigue, which is understood to be due to both peripheral and central mechanisms (Thomas et al., 2015).

Physical fitness and athletic experience have been reported to moderate cognitive performance following exercise (Chang et al., 2012, Voss et al., 2009). Highly trained sports players are able to sustain performance and recover quicker from high-intensity intermittent exercise (Edwards et al., 2003); however, it is known that even well-trained games players become fatigued with increasing game time (Rampinini et al., 2009). As such, the fatigue induced via cumulative exercise bouts in the current protocol may have been above a functional threshold, even for trained players, resulting in the reported detrimental effects on cognitive performance and mood. As most research investigates the effects of exercise during or immediately following one acute exercise session, the present study highlights important novel implications for individuals involved in repeated exercise.

Reductions in sprint time, HR and blood lactate values were observed on day 2 despite no change in effort (as shown by RPE), indicating the presence of exercise-induced fatigue. Reductions in mood, particularly alertness, and increases in mental fatigue were also observed on day 2. Research examining the effect of HIE on mood is limited, particularly in trained populations. It has been suggested that trained

individuals who are accustomed to HIE will find strenuous exercise less aversive than their untrained counterparts (Solomon and Corbit, 1974) and are more positive during exercise at higher intensities than less active individuals (Parfitt et al., 1994). The present study however is in support of others that have reported detrimental effects of multiday consecutive performance on mood, perceptions of fatigue and well-being (Gescheit et al., 2015, Halson et al., 2002, Johnston et al., 2013). Unlike alertness and contentedness in which progressively negative effects of HIE were observed, exercise had positive effects on calmness initially but following one day of HIE negative effects were observed on day 2. Given the recognised relationship between mood and cognitive performance (Ashby and Isen, 1999, Mitchell and Phillips, 2007, Parkinson et al., 1996, Spies et al., 1996), it may be suggested that the reduced mood state on day 2 of the current study contributed to the reductions in cognitive performance. Self-report measures of well-being and physical status are often overlooked in favour of objective physiological and biochemical markers; recent evidence however demonstrates subjective measures are often more responsive to training and provide superior sensitivity and consistency compared to objective counterparts (Saw et al., 2015). As self-report measures are easy to employ, quick to determine and physically non-invasive, they can provide a good indication of immediate player performance and well-being; something of great use during congested periods of competition.

It is acknowledged that laboratory-based exercise does not truly replicate the demands of match performance; it does however, enable greater control over confounding variables. The current protocol was selected based upon a sport-specific intermittent paradigm and was adapted from studies that have used sprint-based protocols in sporting populations (Austin et al., 2013, Howatson and Milak, 2009). Specifically, a running protocol was selected due to it being the exercise mode the trained participants were most familiar with. This is particularly important as meta-analytic assessment has demonstrated that the cognitive response may not be similar between exercise modes (Lambourne and Tomporowski, 2010). Furthermore, it has been shown that familiarity of exercise mode and exercise modality preference influence mood (Daley and Maynard, 2003) and brain cortical activity which may contribute to altered psychophysiological response (Brümmer et al., 2011). Thus, the use of an intermittent high-intensity protocol in the present study may better reflect cognitive performance in intermittent team sports players than studies that have used alternate exercise modalities (McMorris and Graydon, 1997a).

4.5 Practical applications

The present study is the first to investigate the impact of congested strenuous exercise sessions on specific cognitive domains, mood, energy and fatigue states. The protocol in this study was specifically designed around Rugby 7's tournament fixtures which commonly involve 3 games per day for two consecutive days, with the ultimate, and arguably most important game, being the last game of the final day. The findings of reduced inhibition, energy, alertness and increased physical and mental fatigue on the second day highlights several practical applications that may serve to help with performance success and player well-being. Perhaps most importantly is the need for cognitive recovery strategies in-between games and tournament days to help players cognitively and mentally recover. Furthermore, the importance of nutritional and physiological recovery strategies are emphasised to minimise fatigue states and increase alertness.

The current results can be applied to many sports that involve congested tournament fixtures as well as applied to professional occupations. For example, military and emergency response personnel are frequently required to perform operations over several days that require the maintenance of cognitive performance under stressful conditions and high physical loads (Hoffman et al., 2014, Nindl et al., 2007). Further understanding of the impact of these situations on both fundamental and task-specific cognitive processes is crucial for improving sports performance over prolonged periods of time and under stressful conditions. Understanding the behavioural responses to congested HIE and the mechanisms behind them will work towards the identification and development of intervention strategies to attenuate negative responses and prepare both the body and mind for each exercise session, thus enabling optimum performance during training and competition.

4.6 Limitations

Participants were provided with standardised meals during testing days and were asked to ensure they consumed sufficient carbohydrates in the evenings prior to testing; this was done in an attempt to maintain blood glucose and glycogen levels. Pharmacological studies indicate that a low blood glucose concentration is associated with the release of counter-regulatory hormones such as cortisol, and an impairment in cerebral function (Blackman et al., 1990, Mitrakou et al., 1991). Though the influence of this mediator on cognitive performance has not been fully established,

the assessment of blood glucose concentration following each exercise bout may have provided greater insight into the potential reasoning behind the reduction in cognitive performance across day 2.

4.7 Conclusion & perspectives

This study is the first to investigate cognitive performance and mood within a consecutive day repeated-exercise paradigm and provides novel data evidencing detrimental effects of strenuous exercise on cognition in trained and accustomed sporting individuals. The main finding was that cumulative HIE had deleterious effects on choice-reaction time and Stroop incongruent accuracy indicative of inhibitory control as well as mood, energy and fatigue states in trained intermittent team sports players. Supporting the previous two chapters, a reduction was observed across the second day of exercise in tasks requiring executive processes, in addition to mood disturbances and reduced physical performance. Increases in mental fatigue occurred concurrently with deteriorations in 20 m sprint performance despite greater perceived effort. It is postulated that increases in both physical and mental fatigue were integral to the reductions in both cognitive and physical performance, though further research is required to establish the mechanistic underpinnings of these findings. Practical applications of the results are discussed with particular emphasis on cognitive recovery strategies between games and tournament days whilst also highlighting the importance of nutrition and physiological recovery strategies for optimal cognitive performance.

This chapter addressed the third aim of the thesis, to `*investigate the effect of multiple acute high-intensity exercise sessions on cognitive performance, mood, energy and fatigue'.* As the first study assessing a congested tournament scenario on cognitive performance, further research is required to replicate these results to support current observations. It is postulated that the reductions in cognitive performance observed may have negative effects on sporting performance and be indicative of the increased injury rates commonly reported with congested sporting fixtures, though limitations of the study make this inference speculative. While reductions in 20 m sprint time were observed, the inclusion of further sport-specific performance measures would have provided further insight, specifically regarding performance accuracy, and should be considered in future studies. Furthermore, assessing sleep quality may have provided further insight behind the observed reductions in accuracy and thus the assessment of sleep will be considered in the next Chapter.

Chapters 3 and 4 provide evidence that both prolonged and repeated strenuous exercise paradigms have negative effects on executive processes and mood in trained individuals that are accustomed to the respective exercise modes used. Given these findings, there is a rationale to suggest that there may be similar effects following exercise of a more chronic nature. Intensified training camps are common practice for many athletes and are a regular part of training cycles. The findings within this thesis thus far suggest weeks of significantly increased training volume may negatively affect cognitive parameters, mood and sporting performance: this will be explored in the following chapter.

Chapter 5: Two-weeks of intensified training disturbs mood, energy and fatigue states but not cognitive function in trained cyclists

5.1 Introduction

Athletes participating in elite sports are frequently exposed to high training loads, where training volume and intensity are pushed to the limits to maximise performance improvement (Soligard et al., 2016). Although many factors can contribute, the main instrument to improve performance is via training regimen. In many sports, intensified training (IT) camps, where high loads are prescribed with limited recovery, are commonly incorporated into an athletes training regimen. The purpose of this is to impose an accumulative training stress great enough to disturb homeostasis, resulting in a transitory performance reduction followed by a supercompensation effect. Though the physiological and biochemical response to the increased load are well-established (Meeusen et al., 2013), much less is known about the cognitive response following a prolonged two-week intense exercise regimen.

Assessment of the literature on the cognitive effect of strenuous and/or prolonged exercise converges towards an impairment in cognitive performance (Ando et al., 2005, Chmura et al., 1994, Cooper, 1973, Davey, 1973, McMorris et al., 2009, Tomporowski, 2003, Yerkes and Dodson, 1908). In agreement with the findings of chapters 2, 3 and 4, studies suggest that above a certain intensity or duration, cognitive functioning could be disrupted, with particular impairments occurring to higher-order cognitive domains (Dietrich, 2009, Dietrich and Audiffren, 2011, Fery et al., 1997, Grego et al., 2005, Wang et al., 2013). Intense exercise has also been associated with detrimental effects on mood state and feelings of well-being (Berger and Motl, 2000). Although the underlying mechanisms for this are still unclear, it is known that an increase in metabolic load and/or exercise of a prolonged duration is associated with the manifestation of both physical (Millet and Lepers, 2004) and mental fatigue (Van Cutsem et al., 2017), which may contribute to reductions in cognition. For example, Grego et al. (2005) found a prolonged cycling bout reduced trained individuals' cognitive performance while McMorris et al. (2009) found cycling at 80 % maximal power output as compared to 50 % induced significantly more errors on an executive task. Recent emerging evidence suggests that the maintenance of prolonged exercise requires mental effort, which is necessary to inhibit the sensory afferents that arise with physical fatigue (Radel et al., 2017). This suggests that increases in mental fatigue, caused via sustained mental effort, may contribute to reduced cognitive performance during and following exercise-induced fatigue.

In line with this, reports following two-weeks of high-volume training have demonstrated that IT causes detectable reductions in both simple and complex

cognitive processes (Decroix et al., 2016, Dupuy et al., 2010, Rietjens et al., 2005). However, others have failed to find any effect (Jeukendrup et al., 1992, Nederhof et al., 2007) and thus the effect of IT on cognition remains far from being fully understood. Due to the complex interaction between exercise and cognition, there are multiple factors than can affect performance and thus several measures, such as physical performance, mood, stress-recovery balance and body mass should be assessed to gain a holistic understanding of potential disruption. This is particularly pertinent in a training paradigm where numerous factors can influence performance. For example, it has been demonstrated that IT can have negative effects on sleep quality (Killer et al., 2017) and it is reported that following suboptimal sleep, mood and cognitive function decline more rapidly than physical capabilities (Davenne, 2009, Fullagar et al., 2015b).

As indicated in previous systematic (see Chapter 2) and meta-analytic (Chang et al., 2012) reviews, the control of confounding factors is imperative in cognitive studies due to the many influential moderating factors. The differences observed between studies may be due to a number of factors including differences in training load, cognitive tests, athlete fitness/experience level, study control and small sample sizes. As a consequence, there is a need for further research that employs strict control and scientific rigor. Though many sports employ IT regimens, they are particularly common in endurance sports such as cycling, with training camps commonly undertaken by both professionals and amateurs. Thus, in line with the fourth objective of the thesis, the aim of this study was to characterise the effect of a two-week intensified training intervention on cognitive performance and psychological disturbances in trained cyclists. Based on the results observed in chapters 3 and 4 that demonstrated a deterioration in particular cognitive domains, mood, energy and fatigue states following strenuous, prolonged and repeated high-intensity exercise, it was hypothesised that IT would cause significant reductions in cognitive and physical performance alongside psychological disturbances to mood, energy, recovery and fatigue states.

5.2 Methods

5.2.1 Participants

Statistical power was calculated using commercially available software (G*Power v3.1.9, Düsseldorf, Germany) to determine an adequate sample size for this

investigation. Based on a hypothesised effect size of 0.5 (Cohen's d – moderate) for a within-between subject's design, it was estimated that a sample size of 24 would be required to detect significant changes with a two tailed α level of 0.05 and a power of 0.90 (Cohen, 1992). To account for a 10% drop-out rate, twenty-seven well-trained male endurance cyclists that met the inclusion criteria outlined below were recruited to participate in this study. Due to unforeseen circumstances during the testing period, 4 participants had to withdraw prior to study completion; this resulted in a total sample size of 23 participants (age: 29.0 ± 5.7 years; height: 177.6 ± 7.2 cm; weight: 75.0 ± 9.6 kg; $\dot{V}O_{2max}$: 61.8 ± 6.5 $ml \cdot kg^{-1} \cdot min^{-1}$).

Participants were provided with a verbal and written explanation of the study prior to providing written informed consent and completed a questionnaire to assess for eligibility, training history and contraindications. All participants were regularly competing at a minimum of category 3 British road racing standard, had a competitive training history of at least 3 years and were routinely training ≥ 4 days per week. All cyclists were healthy, had no severe head injuries in the past 12 months and did not take any medication that may have interfered with cognitive performance. This study was conducted in accordance with the Helsinki Declaration (1964) and was approved by Northumbria University's Faculty of Health and Life Sciences Ethics committee. All study procedures were conducted in a laboratory accredited by the British Association of Sport and Exercise Sciences.

Following familiarisation participants were randomly assigned, via block randomisation, to the experimental group (intensified training; IT) or the control group (normal training; NT) according to a matched group experimental design based on $\dot{V}O_{2max}$. Group characteristics taken at baseline are presented in Table 5.1. According to the $\dot{V}O_{2max}$ based athlete-classification norms of Pauw et al. (2013), the cyclists could be categorised as performance levels 3 (76 %), 4 (16 %) and 5 (8 %), which can be described as trained, highly trained and professional respectively.

Table 5.1 Baseline characteristics for the normal training (NT) and intensified training (IT) groups

Participant Characteristics	Intensified training (IT, *n* = 12)	Normal training (NT, *n* = 11)	*p*
Age (years)	28.9 ± 6.6	29.2 ± 4.9	0.92
Height (cm)	177.8 ± 7.3	177.3 ± 7.5	0.87
Body mass (kg)	74.8 ± 10.8	75.2 ± 8.6	0.92
$\dot{V}O_{2max}$ (ml/min)	4630.0 ± 618.9	4538.2 ± 601.7	0.72
$\dot{V}O_{2max}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	62.5 ± 7.9	61.1 ± 5.0	0.63
Peak power output (W/kg)	5.8 ± 0.6	5.5 ± 0.4	0.19

All values are mean ± SD

5.2.2 Experimental protocol

Participants were familiarised to all test procedures prior to baseline data collection. This included the completion of a maximal cycle ergometer test (MT) and a 1-hour time trial (TT) alongside three completions of all cognitive tasks and mood scales/questionnaires. No participant exhibited signs of fatigue prior to beginning the study, assessed via visual analogue scales at familiarisation.

The training of each cyclist was monitored for a period of 5 weeks in total, which was divided into three distinct phases. The first phase was the same for both IT and NT groups and consisted of a 1 week baseline period. During this, all cyclists performed and recorded their usual amount and type of training for five days followed by a baseline MT on the sixth day and baseline TT on the seventh day.

The second phase consisted of a 100 % increase in training volume and intensity for the IT group; the NT replicated their usual amount and type of training as performed in the baseline week (Figure 5.1). Participants trained 7 days per week for these 2 weeks including MT and TT laboratory tests, which were performed on the sixth and seventh days respectively. The third phase of the study was similar for both the IT and NT group and consisted of a taper period where baseline training volume was reduced by 50 % for 2 weeks with final performance tests completed on the thirty-fifth and thirty-sixth day of the study.

To ensure that performance variations during all physical and cognitive performance tests were due to the IT period and not to the acute training session(s), all participants were instructed to refrain from exercise 24-hours prior to laboratory visits. Additionally, participants were instructed to abstain from caffeine and alcohol and to eat the same food for 24-hours leading up to each performance test. Subjects were encouraged to consume a carbohydrate-rich diet and to remain euhydrated during the entire experimental period. To monitor compliance, all participants completed a food diary throughout the study period.

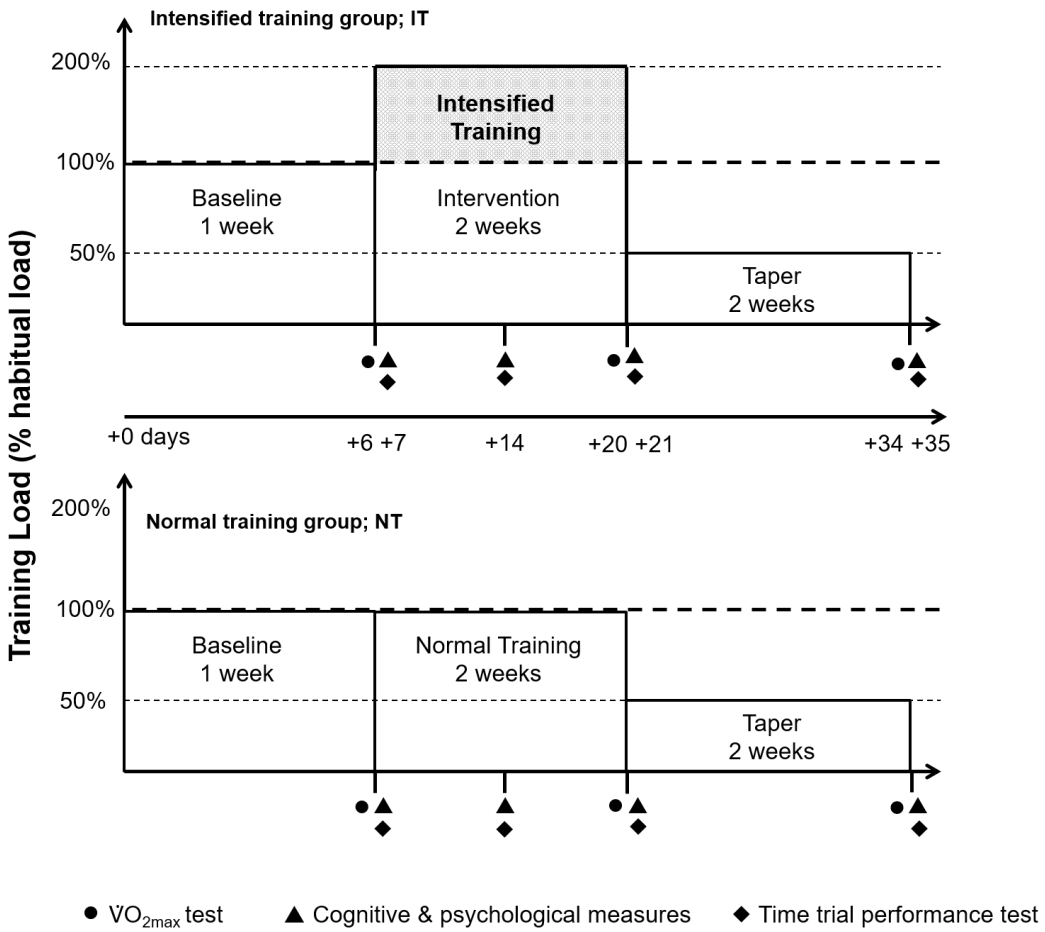

Figure 5.1 Schematic representation of the study design

To examine changes in performance a variety of measures were taken. Participants performed two physical performance tests and four cognitive tests at weekly intervals during the training period alongside measurements of mood, recovery and feelings of mental and physical energy and fatigue, as well as at the end of the taper period. Additionally, due to the intervention type and duration, perceived sleep quality was

assessed throughout each phase of the study. To control for diurnal variation, all testing was performed at the same time of day for each participant. A summary of physical performance, cognitive and psychological assessments completed each week during the study period can be seen in Table 5.2 below.

Table 5.2 Summary of physical performance, cognitive and psychological assessments completed during the study period

Tests	Baseline	Training week 1	Training week 2	Taper week 1	Taper week 2
Body Mass	×	×	×		×
$\dot{V}O_{2max}$	×		×		×
1-hour time trial	×	×	×		×
Cognitive testing	×	×	×		×
Mood	×	×	×		×
Perceived sleep	×	×	×	×	×

5.2.2.1 Training quantification

Each participant received a Polar A300 fitness watch and heart rate monitor (Polar, Kempele, Finland) to record all activity for the duration of the study. Following every training session, participants synchronised their watch with the Polar Flow app for training data to be downloaded; training accounts were monitored daily by the principal investigator to ensure adherence to the specified training hours each week. In addition, participants were instructed to complete an online training diary within the first 30-minutes following every training session. Recoded data included; type of session, time spent in each HR zone from the Polar data, total training time and session rate of perceived exertion (sRPE) which was rated via a 0-10 scale (Foster, 1998). sRPE is one of the most widely used methods to quantify internal training load which accounts for both physiological and psychological stress that results from external load (training volume and intensity) (Foster, 1998). Monitoring both internal and external load provides a more inclusive method to assess training load as many circumstances can influence the ability of an athlete to handle a given external load (Halson, 2014). sRPE and exercise time were used to calculate training load, monotony and strain. The product of the sRPE (0-10) and training duration (in minutes) was termed the daily load. Total weekly load was calculated for each training week by the sum of daily loads. Monotony was computed by dividing the average

daily load by the standard deviation of the daily load. Strain was calculated as total load multiplied by monotony.

To prescribe training load in the IT group, individual baseline training diaries were assessed for total volume and these values were then doubled. HR zones were individually calculated from each participants HR maximum (HR_{max}) measured at the baseline $\dot{V}O_{2max}$ test. Five zones were devised, based on previous research (Halson et al., 2002, Killer et al., 2017), and expressed as a percentage of HR_{max}: zone 1, < 69 % HR_{max}; zone 2, 69-81 % HR_{max}; zone 3, 82-87 % HR_{max}; zone 4, 88-94 % HR_{max}; zone 5, > 94 % HR_{max}.

5.2.3 Cognitive function assessment

Cognitive measures were administered using COMPASS (Northumbria University, UK). The cognitive battery of tests took approximately 15-minutes to complete and included simple reaction time (SRT), four-choice reaction time (FCRT), Corsi block task and the Stroop task. For full descriptions of cognitive tasks please refer to the methods section in Chapter 3. The Stroop task in this study was configured to present 160 random congruent and incongruent stimuli.

5.2.4 Mood assessment

Participants completed three mood/recovery questionnaires on the final day of each training week following cognitive tests. Two of these were the ‘Bond-Lader Mood Scale’ and the ‘Mental and Physical State and Trait Energy and Fatigue Scale’ that asked participants to report, “How do you feel right now”. The description and scoring for these scales can be seen in the methods section of chapter 3.

The Profile of Mood States (POMS-65) was also administered (McNair, 1971, McNair et al., 1992); a 65-item Likert scale questionnaire which measures six specific mood states (tension, depression, anger, vigour, fatigue and confusion). For this questionnaire participants were asked to score how they had been feeling “During the past week, including today”, therefore providing an overall representation of mood over each training week. Data was analysed for each specific mood state and total mood disturbance (TMD) was calculated by the sum of anger, fatigue, depression and tension minus vigour. Higher TMD scores indicate greater negative mood

disruption. A score for energy index was also calculated by subtracting vigour from fatigue. Higher scores for energy index indicate greater feelings of energy.

5.2.5 Recovery-Stress questionnaire

Perceptual measures of stress and recovery were assessed using the recovery stress questionnaire for athletes (RESTQ-Sport) (Kellmann and Kallus, 2001) on the final day of each training week prior to the TT performance. The RESTQ-Sport is a 76 item psychometric questionnaire that systematically assesses an individual's recovery-stress state in both a general and a sport-specific context (Kellmann and Kallus, 2001). The response scale asks participants to rate the frequency of each item over the preceding 3 days/nights on a scale of 0 (never) to 6 (always). These responses form 19 subscales, made up of 12 general scales and 7 sport-specific scales, with 4 questions per scale. Total scores of stress and recovery can be evaluated enabling a holistic perspective of athlete's recovery stress states. The total stress score corresponds to the sum of all the stress subscale scores (7 general plus 3 sport-specific), while the total recovery score represents the sum of all of the recovery subscale scores (5 general plus 4 sport-specific). A general indicator of the recovery-stress state is calculated as the total recovery score minus the total stress score; where higher scores indicate better recovery and less stress. The RESTQ-Sport has been demonstrated to have a good internal consistency (Cronbach's a values range from 0.71 to 0.93) and reports Pearson's (r) test-retest reliability values following 3 and 9 days as 0.51 - 0.81 (Kellmann and Kallus, 2001).

5.2.6 Perceived sleep quality

Intense training is associated with suboptimal sleep, which could have an effect on cognitive functioning. To assess subjective sleep, upon awakening following the fourth, fifth and sixth night's sleep of each training week, participants completed the Karolinska Sleep Diary (KSD) (Åkerstedt et al., 1994). Mean responses over the 3 nights were calculated to account for potential random disturbance. The KSD, which has been validated against polysomnography and has shown significant correlations with objective sleep parameters (Åkerstedt et al., 1994), consists of 12 items, most of which offered 5 response alternatives graded from 5 to 1. Sleep efficiency was calculated as total sleep length/total time in bed (sleep length + sleep latency) whilst number of awakenings per hour was calculated as number of awakenings/sleep

length. The diary was intended to be short, but to reflect the usually encountered sleep disturbances of initiating and maintaining sleep, as well as a global appreciation of sleep. Sleep quality and feeling refreshed are used as global indicators of sleep, whereas the rest of the items covered specific aspects of sleep.

5.2.7 Physiological and performance testing

All cycling performance tests were performed on a magnetically braked cycle ergometer (Velotron, RacerMate Inc., Seattle, USA). Individual cycling positions were recorded following familiarisation and replicated throughout the study. Participants were instructed to drink water ad libitum throughout each test.

5.2.7.1 Time trial

The main performance measure used throughout the study was a 1-hour cycling time trial (TT). This test was selected due to its high ecological validity, low coefficient of variation (CV) and sensitivity to change, enabling it to detect small, but important changes in performance (Currell and Jeukendrup, 2008). Following a 10-minute warm-up at a self-selected pace, participants were asked to “Cover as much distance as possible in 60 minutes”, where they could freely select their gears and cadence. Throughout the TT participants were blinded to all performance data, with the only feedback being an indication every time 10 minutes had been completed. The intra-individual reliability of these measures, assessed in the NT group returned a CV of 1.7 %. Mean power output (MPO), distance and average HR were recorded throughout whilst blood lactate concentration was taken pre and immediately post each TT. RPE was provided immediately following the TT completion.

5.2.7.2 Maximal incremental test ($\dot{V}O_{2max}$)

Following a graded 20-minute warm-up (4-minute incremental stages), the cycle ergometer software (RacerMate® One, RacerMate® Inc.) was programmed to elicit an incremental ramp test which increased at a rate of 4 watts (W) every 10-seconds (24 $W \cdot min^{-1}$); starting power output for each participant was individually prescribed following familiarisation. Participants were instructed to continue cycling for as long as possible and were strongly encouraged throughout. The test was terminated upon voluntary stoppage or until a cadence of at least 60 rpm could not be maintained. Expired gas was collected throughout using an online (i.e. continuously

measured/real time) gas analyser (Metalyzer 3B; Cortex, Leipzig, Germany) to measure oxygen and carbon dioxide fractions and volume of gas in inspired and expired air. The analyser was warmed up and calibrated for oxygen (15 %) and carbon dioxide (5 %) fractions and gas volume (3 L syringe) as per manufacturers prescription. During the tests, the participant breathed through a low dead space (70 mL) mouth piece and low resistance turbine (<0.1 $kPa \cdot L^{-1} \cdot s^{-1}$ at 16 $L \cdot s^{-1}$), while inspired and expired gas was sampled continuously at 50 Hz. Expired gas data were averaged across 30-second intervals using online gas analysis software (MetaSoft Studio, Cortex., Leipzig, Germany), before downloading for subsequent assessment. The W_{max} intra-individual reliability assessed in the NT group returned a CV of 1.9 %. $\dot{V}O_{2max}$ was calculated as the highest 30-second average collected during the maximal test. HR was recorded throughout (Polar, Kempele, Finland) whilst a capillary blood lactate sample and RPE were provided upon immediate completion of the test. According to the British Association of Sport and Exercise Sciences testing guidelines (Winter et al., 2006), the test was considered to be maximal when at least three of the following criteria were met: HR >90 % of HR_{max}, blood lactate >10 mmol/L, respiratory exchange ratio >1.15, respiratory rate >45, no further increase in $\dot{V}O_2$ despite an increase in workload. Peak power output (PPO) was determined as the highest 30-second average from the incremental ramp test and subsequently expressed relative to body mass.

5.2.8 Statistical analysis

All data were analysed using statistical software (IBM SPSS Statistics 24, New York, USA). Prior to analysis, outliers were identified as greater or less than 2.5 times the SD of the mean and removed. The IT and NT groups were statistically compared at baseline using an independent samples t-test to ensure that they were similar prior to the commencement of training; this included physiological variables as seen in Table 5.1. All data were analysed using a two-way repeated measures ANOVA with group as a between subject's factor and time as a within subject's factor. Significant interaction effects were followed up with prior planned pairwise comparisons with LSD to identify significant differences between individual means. Statistical significance was set at an α level of 0.05. Sphericity was assumed if Mauchly's test score returned $p \geq 0.05$; if sphericity was violated, the degrees of freedom were corrected using Greenhouse-Geisser procedure.

5.3 Results

A prerequisite to compare physical performances at different time points in different athletes is to make sure that all performances were indeed maximal. We did not find any effect of time or group on the RPE at the end of each MT or TT ($p<0.05$), thus suggesting that this criterion was fulfilled. Baseline analysis on all measures revealed no differences between groups ($p<0.05$).

5.3.1 Cognitive function

No main or interaction effects were observed on any cognitive variable due to the IT (Table 5.3).

Table 5.3 Cognitive performance (mean ± SD) in IT and NT groups over the course of the training study

Measure	Baseline		Training week 1		Training week 2		Taper		*p* value		
	IT	NT	IT	NT	IT	NT	IT	NT	G	T	X
SRT (ms)	279.6 ± 18.0	280.4 ± 21.4	285.9 ± 22.3	280.1 ± 19.9	292.5 ± 33.5	276.2 ± 14.9	278.1 ± 24.6	275.4 ± 15.7	0.40	0.40	0.35
FCRT correct RT (ms)	511.6 ± 54.5	504.5 ± 65.3	514.4 ± 47.6	507.1 ± 54.3	527.9 ± 55.0	503.4 ± 62.7	503.2 ± 41.7	511.1 ± 63.3	0.72	0.73	0.27
FCRT accuracy (%)	98.4 ± 2.1	98.3 ± 2.1	99.5 ± 1.2	96.9 ± 3.7	99.0 ± 1.5	98.6 ± 2.1	100.0 ± 0.0	98.6 ± 2.1	0.46	0.21	0.12
Corsi blocks (span score)	6.8 ± 0.7	6.2 ± 0.9	6.5 ± 0.8	6.4 ± 0.7	6.8 ± 1.4	6.4 ± 0.9	6.6 ± 1.0	6.5 ± 1.0	0.38	0.87	0.47
Stroop correct RT (ms)	698.5 ± 94.0	690.8 ± 99.8	695.8 ± 114.6	676.4 ± 74.7	698.8 ± 105.3	660.5 ± 81.2	692.1 ± 57.5	663.5 ± 84.0	0.50	0.59	0.70
Stroop accuracy (%)	97.4 ± 1.7	97.4 ± 2.0	98.5 ± 1.2	98.0 ± 1.6	98.1 ± 1.8	97.9 ± 2.5	98.3 ± 1.5	97.9 ± 1.6	0.59	0.50	0.82
Stroop congruent correct RT (ms)	658.5 ± 81.2	668.8 ± 101.3	658.7 ± 107.4	656.1 ± 87.8	666.3 ± 100.2	639.2 ± 78.8	659.1 ± 57.5	655.5 ± 87.5	0.86	0.90	0.63
Stroop congruent accuracy (%)	98.1 ± 2.2	96.9 ± 3.0	98.6 ± 1.5	98.5 ± 1.7	97.6 ± 2.0	98.0 ± 2.9	98.4 ± 1.4	98.1 ± 1.3	0.60	0.20	0.44
Stroop incongruent correct RT (ms)	739.9 ± 111.0	712.5 ± 104.9	732.9 ± 123.3	697.0 ± 66.2	746.4 ± 118.5	682.1 ± 84.6	725.1 ± 69.6	671.5 ± 85.0	0.27	0.28	0.70
Stroop incongruent accuracy (%)	96.8 ± 2.2	97.8 ± 1.6	98.4 ± 1.5	97.4 ± 2.1	98.4 ± 2.1	98.0 ± 2.5	98.1 ± 1.9	97.7 ± 2.0	0.73	0.28	0.14

G = group; T = time; X = interaction

5.3.2 Mood, energy, fatigue and recovery states

5.3.2.1 Profile of Mood States

A time main effect ($F_{(2,42)}$=9.84, p<0.001, η_p^2=0.32) and group x time interaction ($F_{(2,42)}$=7.92, p=0.001, η_p^2=0.27) for TMD was observed. Pairwise comparisons showed TMD was significantly greater in the IT group compared to the NT group (p<0.05) and baseline (p<0.001) during both IT weeks. A time main effect ($F_{(3,63)}$=19.42, p<0.001, η_p^2=0.48) and interaction effect ($F_{(3,63)}$=12.78, p<0.001, η_p^2=0.39) was also observed for energy index, with pairwise comparisons demonstrating significantly lower energy in the IT group compared to the NT group during training week 1 (TW1; p=0.002) and training week 2 (TW2; p=0.001) as well as significant reductions in energy index compared to baseline (p<0.001; Figure 5.2). In the IT group, TMD and energy index were significantly improved following the taper compared to TW2 (p<0.001).

Table 5.4 shows mean weekly POMS scores for each subscale. Significant interaction effects were found for vigour ($F_{(3,63)}$=6.10, p=0.002, η_p^2=0.26), fatigue ($F_{(2,47)}$=16.58, p<0.001, η_p^2=0.44) and confusion ($F_{(2,41)}$=8.45, p=0.001, η_p^2=0.29). Post-hoc analysis showed vigour to be significantly lower than the NT group during TW1 (p=0.016) and lower during both TW1 (p=0.001) and TW2 (p=0.003) compared to baseline. Similarly, fatigue was significantly higher in the IT group during TW1 (p=0.006) and TW2 (p<0.001) compared to the NT group and was significantly lower than baseline during both IT weeks (p<0.001). Participants in the IT group also felt significantly more confused during TW2 (p=0.015) compared to the NT and during TW1 (p=0.021) and TW2 (p=0.001) compared to baseline.

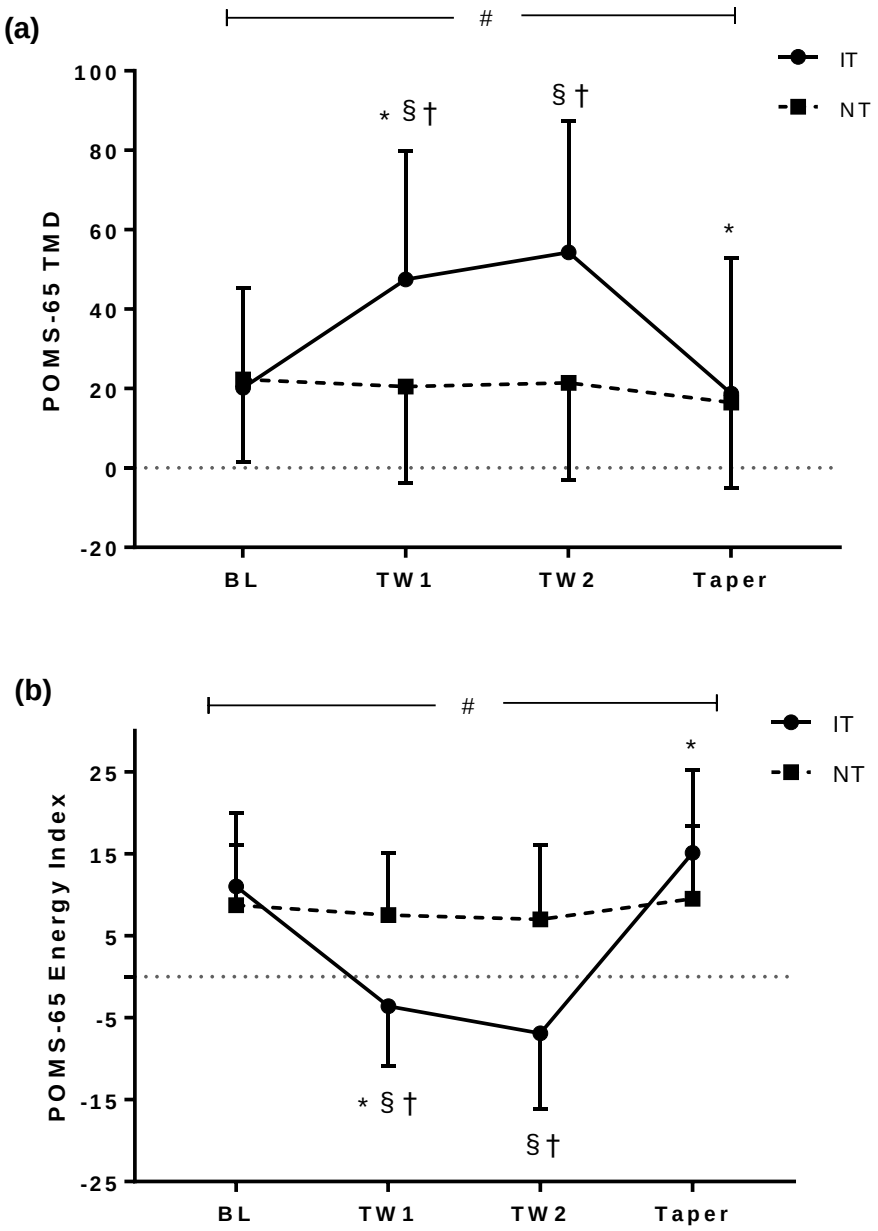

Figure 5.2 Change in (a) total mood disturbance and (b) energy index. Data presented as mean ± SD. *Significantly different to previous measure (p<0.001); †significantly different to baseline week (p<0.001); §significant difference between IT and NT groups (p<0.05); #significant time main effect (p<0.001)

Table 5.4 Changes in Profile of Mood State subscales measured in IT and NT cyclists throughout the study period

Measure	Baseline		Training week 1		Training week 2		Taper		*P* value		
	IT	NT	IT	NT	IT	NT	IT	NT	Group	Time	X
Tension	8.8 ± 4.8	6.6 ± 4.3	11.2 ± 6.7	6.5 ± 4.2	11.8 ± 6.4	6.6 ± 4.7	9.3 ± 6.7	6.3 ± 3.9	0.07	0.25	0.32
Depression	5.9 ± 6.0	7.5 ± 6.6	10.4 ± 9.6	7.1 ± 6.4	10.6 ± 8.6	7.0 ± 6.3	7.2 ± 7.9	5.6 ± 5.3	0.52	0.09	0.19
Anger	8.4 ± 4.8	7.9 ± 6.0	11.6 ± 8.5	7.2 ± 3.2	12.1 ± 8.6	7.2 ± 4.6	10.6 ± 8.7	6.4 ± 3.4	0.11	0.65	0.35
Vigour	18.6 ± 5.1	17.7 ± 4.6	13.5 ± 3.4 *†§	17.1 ± 3.2	13.4 ± 5.2†	15.5 ± 5.3	20.2 ± 4.9*§	15.6 ± 4.8	0.97	0.001	0.002
Fatigue	7.6 ± 5.1	9.0 ± 4.6	17.1 ± 5.3*†§	9.6 ± 6.3	20.3 ± 4.7*†§	8.5 ± 5.2	5.1 ± 5.7*	6.2 ± 4.7	0.02	<0.001	<0.001
Confusion	8.0 ± 4.7	9.0 ± 3.0	10.8 ± 4.8*†	7.2 ± 3.8	12.8 ± 5.3*†§	7.5 ± 4.2	6.7 ± 4.1 *	7.7 ± 4.0	0.28	0.012	0.001

Data presented as mean ± SD. *Significantly different to previous measure (p<0.05); †significantly different to baseline week (p<0.05); §significant difference between IT and NT groups (p<0.05). X = interaction

5.3.2.2 Bond-Lader Mood Scale

A time main effect was observed for alertness ($F_{(3,63)}$=9.34, p<0.001, η_p^2=0.31), contentedness ($F_{(3,63)}$=4.99, p=0.004, η_p^2=0.19) and calmness ($F_{(3,63)}$=6.02, p=0.001, η_p^2=0.22). Significant group x time interaction effects were observed for alertness ($F_{(3,63)}$=7.70, p<0.001, η_p^2=0.27), contentedness ($F_{(3,63)}$=5.52, p=0.002, η_p^2=0.21) and calmness ($F_{(3,63)}$=3.34, p=0.025, η_p^2=0.14)(Figure 5.3). Post-hoc analysis on alertness revealed significantly reduced feelings of alertness in the IT group during TW1 (p<0.001) and TW2 (p=0.001) compared to baseline and during TW1 (p=0.001) and TW2 (p=0.031) compared to NT. In addition, the IT group had reductions in feelings of contentedness at TW1 (p=0.03) and TW2 (p=0.001) compared to baseline. There were no group differences in feelings of calmness though participants in the IT group felt significantly less calm following the recovery period compared to baseline (p=0.01). Apart from feelings of calmness, no significant differences in the IT group were observed between baseline and the taper period, demonstrating a return to baseline.

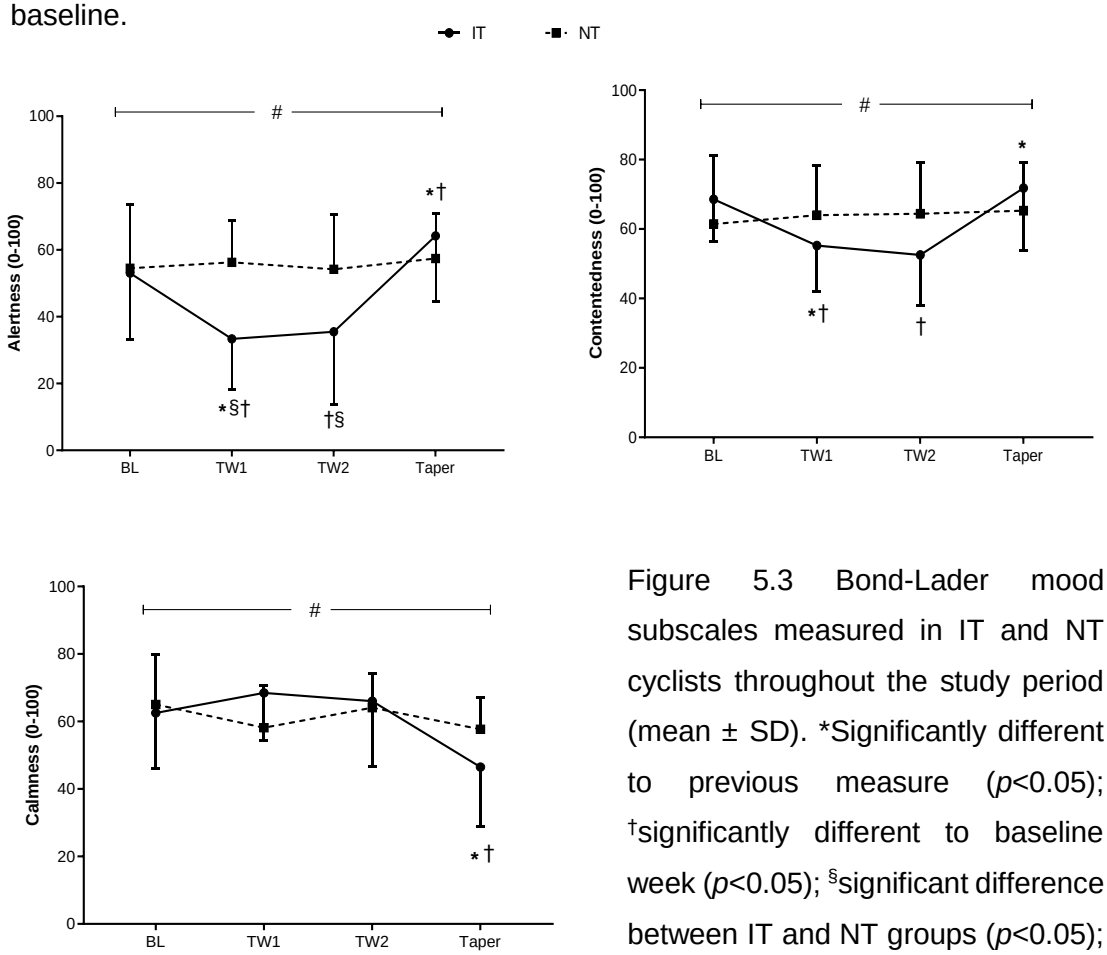

Figure 5.3 Bond-Lader mood subscales measured in IT and NT cyclists throughout the study period (mean ± SD). *Significantly different to previous measure (p<0.05); †significantly different to baseline week (p<0.05); §significant difference between IT and NT groups (p<0.05); #significant time main effect (p<0.05).

5.3.2.3 Mental and physical state and trait energy and fatigue scale

Changes in participant's ratings of physical and mental energy and fatigue across the study period are shown in Figure 5.3. Significant time x group interaction effects were observed for ratings of physical energy ($F_{(3,63)}$=13.20, p<0.001, η_p^2=0.39), physical fatigue ($F_{(3,63)}$= 14.94, p<0.001, η_p^2=0.52), mental energy ($F_{(2,38)}$=7.63, p=0.002, η_p^2=0.27) and mental fatigue ($F_{(3,63)}$=8.40, p<0.002, η_p^2=0.21). Pairwise comparisons revealed significantly greater physical and mental fatigue and reduced physical and mental energy during both TW1 (p<0.005) *and* TW2 (p<0.005) compared to the NT group and baseline. Physical energy was significantly greater in the IT group compared to baseline and TW2 following the taper period (p<0.005). All other variables returned to baseline following the taper.

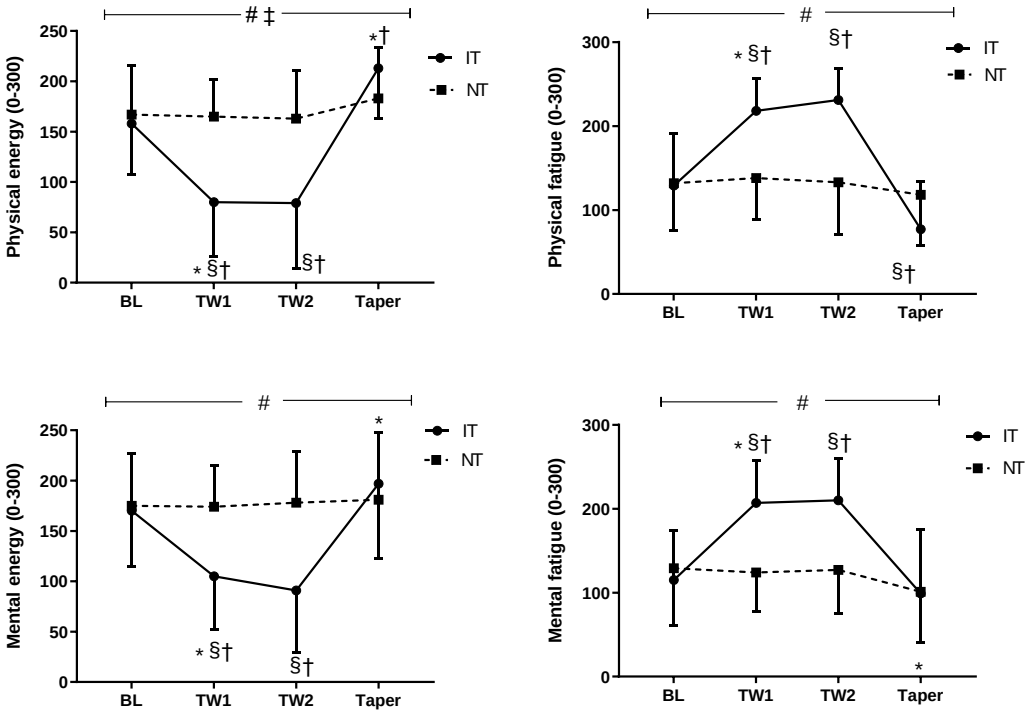

Figure 5.4 Physical and mental energy and fatigue ratings across the study period. Data presented as mean ± SD. *Significantly different to previous measure (p<0.001). §Significantly different between conditions (p≤0.001). †Significantly different to baseline week (p<0.005). #Time main effect (p<0.001). ‡Group main effect (p<0.05)

5.3.2.4 RESTQ-Sport questionnaire

Changes in each subscale of the RESTQ-Sport and the composite scales can be seen in Table 5.5. During the IT period, significant interaction effects were observed for total stress ($F_{(2,44)}$=19.53, p<0.001, η_p^2=0.48), total recovery ($F_{(3,63)}$=4.87, p<0.005, η_p^2=0.19) and recovery-stress state ($F_{(2,44)}$=13.96, p<0.001, η_p^2=0.40). Pairwise comparisons revealed significant increases in total stress and decreases in total recovery in the IT group during TW1 (p<0.01) and TW2 (p<0.005) compared to baseline with total stress also being significantly greater than NT during both IT weeks (p<0.005). Accordingly, the recovery-stress state in the IT group was significantly affected during both intensified weeks compared to baseline (p<0.001) and the NT group (p<0.05; Figure 5.4).

Significant interaction effects were found for individual stress subscales including; fatigue ($F_{(2,49)}$=12.64, p<0.001, η_p^2=0.38), lack of energy ($F_{(3,63)}$=7.85, p<0.001, η_p^2=0.27), physical complaints ($F_{(3,63)}$ = 11.97, p<0.001, η_p^2= 0.43), disturbed breaks ($F_{(2,48)}$=12.50, p<0.001, η_p^2=0.37), emotional exhaustion ($F_{(3,63)}$=6.252, p=0.001, η_p^2=0.23) and fitness/injury ($F_{(2,44)}$=22.62, p<0.001, η_p^2=0.52), and for individual recovery scales; success ($F_{(3,63)}$=3.77, p=0.015, η_p^2=0.15), physical recovery ($F_{(3,63)}$=4.40, p=0.007, η_p^2=0.17), being in shape ($F_{(3,63)}$=7.64, p<0.001, η_p^2=0.27) and self-efficacy ($F_{(3,63)}$=3.65, p=0.02, η_p^2=0.15). All stress subscales were significantly increased during the intensified period in the IT group compared to baseline (p<0.05) and to the NT group (p<0.05). Recovery subscales of physical recovery, being in shape and self-efficacy were all reduced compared to baseline in the IT group (p<0.05) apart from success which did not change.

Following the taper period total stress and stress subscales including; lack of energy, physical complaints and fitness/injury were significantly lower than baseline in the IT group (p<0.05) while the recovery scale, being in shape, was significantly greater than baseline (p=0.008). No significant differences in the IT group were observed between baseline and the taper period in all other subscales and composite scales, demonstrating a return to baseline (all p<0.05).

Table 5.5 RESTQ-Sport subscales of stress and recovery in IT and NT groups over the course of the training study

Measure	Baseline		Training week 1		Training week 2		Taper		*p* value		
	IT	NT	IT	NT	IT	NT	IT	NT	Group	Time	X
Stress subscales											
General stress	0.9 ± 0.9	1.1 ± 1.1	1.4 ± 1.0*†	0.9 ± 0.5	1.5 ± 1.2†	0.9 ± 0.5	1.0 ± 1.0*	0.8 ± 0.7	0.41	0.28	0.05
Emotional stress	1.6 ± 0.7	1.3 ± 0.8	2.1 ± 1.1	1.3 ± 0.7	2.3 ± 1.1	1.2 ± 0.8	1.6 ± 1.3	1.2 ± 0.8	0.07	0.08	0.06
Social stress	1.4 ± 0.7	1.5 ± 1.2	1.8 ± 1.1	1.1 ± 0.8	2.1 ± 1.1	1.3 ± 0.6	1.8 ± 1.4	1.4 ± 0.9	0.20	0.56	0.23
Conflicts/Pressure	2.7 ± 0.8	2.5 ± 1.4	2.7 ± 0.8	2.1 ± 0.8	3.0 ± 0.5§	2.0 ± 1.1	2.4 ± 1.0*	1.8 ± 0.9	0.09	0.014	0.12
Fatigue	1.8 ± 1.0	2.4 ± 1.2	3.5 ± 1.2*†§	1.8 ± 1.0	3.8 ± 0.9†§	2.2 ± 0.9	1.9 ± 1.0*	1.9 ± 1.3	0.048	<0.001	<0.001
Lack of energy	2.3 ± 1.3	2.1 ± 1.0	3.0 ± 1.0*†§	2.1 ± 0.8	3.5 ± 1.3†§	2.1 ± 0.6	1.6 ± 0.7*†	2.0 ± 1.0	0.13	<0.001	<0.001
Physical complaints	1.5 ± 1.0	1.7 ± 1.2	2.9 ± 1.1*†§	1.5 ± 0.9	3.1 ± 1.1†§	1.4 ± 0.8	0.9 ± 0.6*†	1.1 ± 0.9†	0.04	<0.001	<0.001
Disturbed breaks	1.0 ± 0.6§	1.8 ± 1.0	2.6 ± 1.0*†	1.3 ± 0.8§	2.7 ± 1.4†	1.3 ± 0.6§	0.8 ± 0.5*	0.8 ± 0.7†	0.11	<0.001	<0.001
Emotional exhaustion	1.1 ± 1.1	1.5 ± 0.9	2.5 ± 1.5*†	1.8 ± 2.0	2.9 ± 1.6†§	1.0 ± 0.8	1.0 ± 1.3*	0.6 ± 0.5†	0.14	<0.001	<0.001
Fitness/injury	1.7 ± 1.1	2.3 ± 1.3	3.5 ± 1.4*†§	1.8 ± 1.4	3.9 ± 1.1*†§	1.4 ± 1.2†	1.0 ± 0.6*†	1.4 ± 1.0†	0.053	<0.001	<0.001

Table 5.5 RESTQ-Sport subscales of stress and recovery in IT and NT groups over the course of the training study (continued)

Measure	Baseline		Training week 1		Training week 2		Taper		*p* value		
	IT	NT	IT	NT	IT	NT	IT	NT	Group	Time	X
Recovery subscales											
Success	3.0 ± 1.1	3.2 ± 1.0	2.6 ± 0.8	3.3 ± 1.1	2.5 ± 0.9	2.5 ± 0.8*†	3.3 ± 0.9*	2.8 ± 0.9	0.82	0.005	0.015
Social recovery	3.3 ± 1.4	3.2 ± 1.4	3.1 ± 1.5	3.0 ± 1.1	2.6 ± 1.1	3.1 ± 1.3	3.3 ± 1.4	2.8 ± 1.1	0.88	0.18	0.08
Physical recovery	3.2 ± 1.2	3.2 ± 1.1	2.4 ± 1.0*†	3.2 ± 1.0	2.2 ± 1.2†	3.1 ± 0.8	3.5 ± 1.0*	3.1 ± 1.1	0.40	0.004	0.007
General well-being	3.8 ± 1.1	3.5 ± 1.3	3.2 ± 1.2	3.5 ± 1.0	2.7 ± 0.8	3.0 ± 1.2	3.8 ± 1.2	3.2 ± 1.0	0.90	0.003	0.06
Sleep quality	3.0 ± 1.7	3.4 ± 1.4	2.7 ± 1.4	3.3 ± 1.7	2.5 ± 1.4	3.2 ± 1.3	2.7 ± 1.1	3.0 ± 1.3	0.33	0.47	0.87
Being in shape	3.5 ± 1.2	3.1 ± 1.0	2.2 ± 1.0*†	3.1 ± 1.2	1.8 ± 1.2†§	2.9 ± 1.2	4.2 ± 1.1*†§	3.3 ± 0.9	0.61	<0.001	<0.001
Personal accomplishment	2.7 ± 1.5	2.6 ± 1.3	2.5 ± 0.7	2.8 ± 0.9	2.0 ± 1.0	2.4 ± 1.1	2.6 ± 1.5	2.3 ± 0.8	0.81	0.13	0.33
Self-efficacy	3.4 ± 1.2	3.4 ± 1.0	2.8 ± 0.9*†	3.4 ± 1.1	2.5 ± 1.0†	3.2 ± 1.0	3.8 ± 1.2*	3.3 ± 0.9	0.52	0.006	0.017
Self-regulation	3.8 ± 1.4	3.6 ± 1.0	3.8 ± 1.1	3.5 ± 1.0	3.2 ± 1.2	3.3 ± 1.0	4.1 ± 1.4	3.7 ± 0.9	0.51	0.038	0.71
Composite scores											
Total stress score	3.0 ± 1.3	3.7 ± 1.7	5.3 ± 1.7*†§	3.2 ± 1.7	5.9 ± 1.9†§	2.9 ± 1.1	2.5 ± 1.4*†	2.4 ± 1.3	0.051	<0.001	<0.001
Total recovery score	6.6 ± 2.1	6.5 ± 1.8	5.6 ± 1.5*†	6.4 ± 1.8	4.9 ± 1.7*†	5.9 ± 1.7	7.0 ± 1.9*†	6.1 ± 1.7	0.75	<0.001	0.004

Data presented as mean ± SD. *Significantly different to previous measure (p<0.05). †Significantly different to baseline week (p<0.05). §Significantly different between conditions (p<0.05). X = interaction

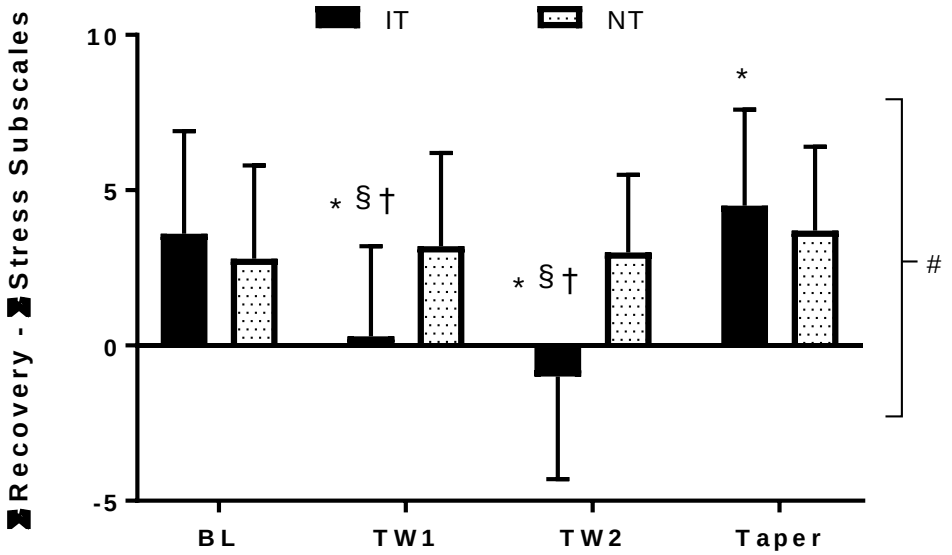

Figure 5.5 RESTQ-Sport recovery-stress measures in the IT and NT group across the study period. Data presented as mean ± SD. *Significantly different to previous measure (p<0.05). §Significantly different between conditions (p<0.05). †Significantly different to baseline week (p<0.001). #Time main effect (p<0.001)

5.3.3 Perceived Sleep

All data obtained from the KSD are presented in Table 5.6. Significant group main effects indicated that the IT group had lower 'calm sleep' ($F_{(1,21)}$=6.67, p=0.017, η_p^2= 0.24), poorer 'sleep efficiency' ($F_{(1,21)}$=6.37, p=0.020, η_p^2= 0.23) and a greater 'number of awakenings per hour' ($F_{(1,21)}$=4.62, p=0.043, η_p^2= 0.18) compared to the NT group. Time main effects were observed for 'sleep quality ($F_{(4,84)}$=3.17, p=0.018, η_p^2= 0.13) and feeling refreshed ($F_{(1,21)}$=3.03, p=0.022, η_p^2= 0.13).

Table 5.6 Changes in perceived sleep measured in IT and NT cyclists throughout the study period

Measure	Baseline		Training week 1		Training week 2		Taper week 1		*Taper week 2*		*P* value		
	IT	**NT**	**IT**	**NT**	**IT**	**NT**	**IT**	**NT**	**IT**	**NT**	**G**	**T**	**X**
Sleep quality[1]	3.5 ± 0.7	3.9 ± 0.8	3.2 ± 0.6	3.9 ± 0.7	3.3 ± 0.7	3.5 ± 0.5	3.8 ± 0.6	3.9 ± 0.7	3.2 ± 1.0	3.7 ± 0.6	0.11	0.02	0.22
Feeling refreshed[1]	3.1 ± 0.7	3.4 ± 0.6	2.6 ± 0.7	3.4 ± 0.9	2.8 ± 0.7	3.2 ± 0.8	3.2 ± 0.7	3.6 ± 0.9	3.0 ± 0.7	3.2 ± 0.8	0.12	0.02	0.20
Calm sleep[1]	3.5 ± 0.6	4.0 ±0.7	2.9 ± 0.8	3.9 ± 0.8	3.3 ± 0.7	3.7 ± 0.6	3.5 ± 0.8	3.8 ± 0.9	2.9 ± 0.9	3.8 ± 0.9	0.02‡	0.08	0.40
Slept throughout[1]	3.8 ± 0.9	4.2 ± 0.8	3.6 ± 1.0	4.1 ± 0.9	3.9 ± 0.9	3.9 ± 0.9	3.9 ± 0.9	4.3 ± 0.5	3.7 ± 0.9	3.9 ± 0.9	0.29	0.64	0.65
Ease of wakening[1]	3.3 ± 0.9	3.3 ± 1.2	2.9 ± 0.9	3.2 ± 1.1	2.6 ± 0.6	3.2 ± 1.1	3.1 ± 0.6	3.2 ± 1.2	3.0 ± 0.8	3.4 ± 0.9	0.36	0.30	0.52
Ease of falling asleep[1]	3.7 ± 1.0	4.3 ± 0.8	3.7 ± 1.0	4.0 ± 0.7	3.8 ± 1.0	4.1 ± 0.5	3.8 ± 0.7	4.4 ± 0.6	3.7 ± 1.1	4.0 ± 0.9	0.09	0.70	0.76
Amount of dreaming[1]	1.8 ± 0.8	1.9 ± 0.7	2.2 ± 1.3	1.9 ± 0.7	1.8 ± 0.9	1.8 ± 0.8	1.9 ± 1.0	1.7 ± 1.0	2.1 ± 1.0	1.7 ± 0.7	0.57	0.82	0.74
Number of awakenings[1]	2 ± 2	1 ± 1	2 ± 1	1 ± 1	2 ± 1	1 ± 1	1 ± 1	1 ± 1	2 ± 1	1 ± 1	0.08	0.12	0.38
Sleep efficiency (%)	96.8 ± 2.7	98.3 ± 1.2	96.0 ± 2.5	97.8 ± 1.9	95.1 ± 5.1	98.3 ± 1.3	96.0 ± 2.3	98.7 ± 1.3	95.2 ± 5.3	97.6 ± 2.2	0.02‡	0.45	0.75
Number of awakenings per hour	0.3 ± 0.2	0.1 ± 0.1	0.2 ± 0.2	0.1 ± 0.2	0.2 ± 0.1	0.1 ± 0.1	0.2 ± 0.1	0.1 ± 01	0.2 ± 0.1	0.1 ± 0.1	0.04‡	0.08	0.60

Data presented as mean ± SD. ‡Significant group main effect (p<0.05). G = group; T = time; X = interaction. [1] Assessed on a scale of 1-5.

5.3.4 Training variables

Post-hoc analysis following a significant interaction effect ($F_{(3,58)}$=70.49, p=0.001, η_p^2=0.77) demonstrated a significant increase in weekly training volume in the IT group during the two-week IT period (110 and 108 % respectively) compared to baseline (p<0.001) and the NT group (p<0.001), who kept their training the same as their normal baseline regimen (5 and 3 % BL increase respectively) (Table 5.7). As a result, the large increase in training volume in the IT group resulted in a significant interaction effect for training load ($F_{(3,53)}$=20.06, p<0.001, η_p^2=0.54) and strain ($F_{(2,42)}$=15.60, p<0.001, η_p^2=0.43) indicating a significant increase in the individual training load (~116 %) and training strain (~151 %) compared to baseline (p<0.001) and the NT group (p<0.005). During the taper period training volume was significantly reduced by 50 % baseline values in both groups (p<0.001) which reduced training load (p<0.001) and strain (p<0.001). A significant time main effect ($F_{(4,84)}$=20.59, p<0.001, η_p^2=0.50) was observed for training monotony with no group or interaction effect.

Body mass did not change in either group throughout the study period (all p<0.05; Table 5.8).

Table 5.7 Training descriptives for weekly training duration, load, monotony and strain in the IT and NT groups throughout the study period

	Baseline	Training week 1	Training week 2	Taper week 1	Taper week 2	*p* value		
						Group	Time	X
Training duration (minutes)								
IT	524.0 ± 96.6	1102.9 ± 222.1*†§	1090.8 ± 167.0†§	275.7 ± 89.4*†	297.7 ± 67.6†	<0.001	<0.001	<0.001
NT	574.8 ± 69.1	606.1 ± 107.0	590.0 ± 79.6	267.7 ± 64.5*†	314.9 ± 62.9*†			
Training load (AU)								
IT	2870 ± 745	6111 ± 1645*†§	6278 ± 1865†§	1516 ± 747*†	1677 ± 464†	0.004	<0.001	<0.001
NT	3346 ± 609	3571 ± 1096	3279 ± 774	1353 ± 466*†	1965 ± 509*†			
Training monotony (AU)								
IT	1.2 ± 0.4	1.6 ± 0.6	1.4 ± 0.4	0.7 ± 0.2	0.9 ± 0.2	0.13	0.001	0.10
NT	1.1 ± 0.5	1.2 ± 0.4	1.2 ± 0.4	0.8 ± 0.3	0.8 ± 0.3			
Training strain (AU)								
IT	3684 ± 1029	9852 ± 4398*†§	8626 ± 3418†§	1108 ± 950*†	1520 ± 462*†	0.001	<0.001	<0.001
NT	3684 ± 1329	4068 ± 1278	3831 ± 1372	1055 ± 629*†	1553 ± 608*†			

Data presented as mean ± SD. *Significantly different to previous measure (p<0.05); †significantly different to baseline week (p<0.05); §significant difference between IT and NT groups (p<0.05). X = interaction

Table 5.8 Body mass in IT and NT groups over the course of the study period

	Baseline		Training week 1		Training week 2		Taper		*p* value		
	IT	**NT**	**IT**	**NT**	**IT**	**NT**	**IT**	**NT**	**Group**	**Time**	**X**
Body mass (kg)	74.8 ± 10.8	75.2 ± 8.6	74.9 ± 11.3	74.6 ± 8.5	74.7 ± 10.9	74.7 ± 7.9	74.6 ± 11.2	74.6 ± 7.7	0.99	0.41	0.43

Data presented as mean ± SD. X = interaction

5.3.5 Performance tests

High-intensity exercise performance ($\dot{V}O_{2max}$) following intensified training in the IT group fell significantly compared to baseline performance, with reductions in PPO (p<0.001; Figure 5.5), HR_{max} (p<0.001) and maximum blood lactate concentration (p=0.001). No changes were observed in the NT group between baseline and the end of the training period. Though a time main effect was observed ($F_{(2,42)}$=5.55, p=0.007, η_p^2=0.21), IT did not result in a significant reduction in absolute $\dot{V}O_{2max}$ compared to baseline. Reductions in TT performance following intensified training in the IT group, but not the NT group, were also observed with declines in MPO (p<0.001), average HR (p<0.001) and post-TT blood lactate concentration (p=0.002). No significant differences in the IT group were observed between baseline and the taper period following both the $\dot{V}O_{2max}$ and TT performance tests, demonstrating a return to baseline following the taper period (Table 5.9).

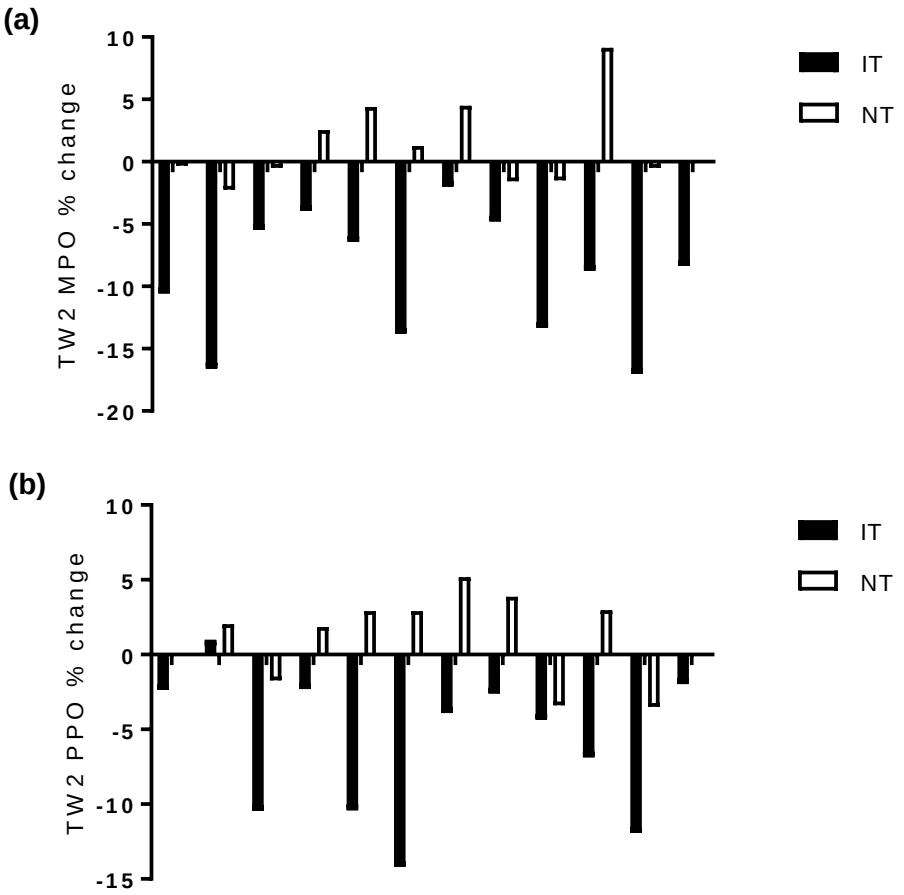

Figure 5.6 Training week two individual (a) MPO and (b) PPO percentage change from baseline in the TT and MT respectively

Table 5.9 Changes in $\dot{V}O_{2max}$ and TT test variables in IT and NT groups over the course of the study period

Measure	Baseline		Training week 1		Training week 2		Taper		*p* value		
	IT	**NT**	**IT**	**NT**	**IT**	**NT**	**IT**	**NT**	**Group**	**Time**	**X**
$\dot{V}O_{2max}$											
$\dot{V}O_{2max}$ (ml/min)	4630 ± 618	4538 ± 601	-	-	4374 ± 577	4473 ± 606	4577 ± 493	4534 ± 646	0.96	0.007	0.17
$\dot{V}O_{2max}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	62.5 ± 7.9	61.1 ± 5.0	-	-	59.1 ± 7.7	60.1 ± 5.0	61.8 ± 6.2	60.8 ± 5.7	0.85	0.005	0.17
PPO (W)	426.8 ± 55.0	409.5 ± 45.1	-	-	406.4 ± 55.7*†	414.2 ± 45.2	430.2 ± 49.2*	421.8 ± 47.0†	0.73	<0.001	<0.001
HR_{max} ($b \cdot min^{-1}$)	188 ± 7	187 ± 9	-	-	181 ± 8*†	186 ± 9	191 ± 6*†	189 ± 10	0.85	<0.001	<0.001
BLa_{max} (mmol/L)	12.7 ± 1.6	12.5 ± 1.5	-	-	10.4 ± 2.0*†§	12.6 ± 1.5	13.0 ± 2.0*	12.3 ± 1.7	0.44	0.018	0.004
RPE	10 ± 1	10 ± 1	-	-	10 ± 1	10 ± 1	10 ± 0	9.7 ± 0.9	0.66	0.41	0.58
TT											
Distance (km)	37.6 ± 2.2	36.4 ± 1.7	36.2 ± 2.7*†	36.5 ± 1.6	36.2 ± 2.1†	36.6 ± 1.5	37.5 ± 2.2*	36.9 ± 1.5	0.72	0.001	0.009
MPO (Watts)	276.2 ± 45.8	253.3 ± 30.4	260.7 ± 49.0*†	254.4 ± 29.4	250.2 ± 40.1†	256.4 ± 28.0	277.4 ± 46.5*	265.5 ± 28.0†	0.58	<0.001	0.007
HR_{av} (bpm)	164 ± 8	155 ± 10	147 ± 16*†	157 ± 11	147 ± 12†	154 ± 9	166 ± 7*	162 ± 8†	0.76	<0.001	<0.001
BLa_{rest} (mmol/L)	1.6 ± 0.4	1.5 ± 0.5	1.4 ± 0.6	1.4 ± 0.4	1.5 ± 0.4	1.5 ± 0.4	1.3 ± 0.4	1.3 ± 0.3	0.73	0.13	0.25
BLa_{max} (mmol/L)	6.5 ± 2.8	5.7 ± 3.1	4.5 ± 2.9*†	6.0 ± 2.6	3.5 ± 2.5†	5.5 ± 2.7	6.0 ± 2.4*	6.0 ± 2.3	0.48	0.006	0.014
RPE	9 ± 1	8 ± 1	8 ± 1	8 ± 1.0	9 ± 1	8 ± 1	9 ± 1	8.7 ± 1.1	0.54	0.07	0.92

Data presented as mean ± SD. *Significantly different to previous measure ($p<0.05$); †significantly different to baseline week ($p<0.05$). BLa_{max} = maximum blood lactate concentration; BLa_{rest} = blood lactate concentration at rest; HR_{av} = average heart rate; HR_{max} = maximum heart rate; PPO = peak power output; RPE = rate of perceived exertion; $\dot{V}O_{2max}$ = maximum oxygen uptake. X = interaction

5.4 Discussion

The primary purpose of this study was to explore the exercise-cognition interaction by characterising the effect of a two-week IT period, immediately followed by a two-week taper period, on cognitive function in trained cyclists. A secondary objective was to evaluate the effect of this training protocol on psychological disturbances including mood, recovery state and feelings of physical and mental energy and fatigue as well as physical disturbances in performance.

Training volume in the IT group was successfully increased by an average of 109 %, as well as an average increase of 116 % in training load and 151 % in training strain compared to the NT group. In line with this increase in volume, the performance data indicated significant fatigue states during both training weeks in the IT group. Compared to baseline, reductions were observed in PPO (-5 %), HR_{max} (-4 %), and BLa_{max} (-18 %). The reduction in PPO observed in the current study is similar to the 5.4 % decrement reported by Halson et al. (2002) following a similar protocol after 2-weeks of IT. Furthermore, reductions in MPO of 6 % and 9 % were observed during the TT following each intensified week alongside reduced average HR and reduced post-TT blood lactate values. There was a daily variation in the NT group of 1.9 % and 1.7 % for the $\dot{V}O_{2max}$ test and TT respectively, thus indicating that the decline in performance was most likely due to the effects of the intensified protocol.

Despite substantially increasing training volume and significantly impairing physical performance, no change in cognitive performance was observed over the study period. These results are in line with others who similarly found no change in cognitive function following a period of IT (Jeukendrup et al., 1992, Nederhof et al., 2007). Physical fitness and athletic status are known moderators of cognitive performance (Chang et al., 2012, Voss et al., 2009) and thus, it could be suggested that the failure to observe any change in cognitive performance may be due to the trained and experienced athletic population recruited for this study. However, studies have reported detrimental effects of IT on cognition in trained and professional cyclists (Decroix et al., 2016, Rietjens et al., 2005) whilst others have found no change in recreational cyclists (ten Haaf et al., 2017) and thus, it seems unlikely that fitness or performance level account for the lack of effect in the current study.

It is understood that during both acute fatiguing exercise (Millet and Lepers, 2004) and prolonged IT (Meeusen et al., 2013), central and peripheral fatigue manifests. It

is generally considered that central fatigue is a consequence of inadequate neurotransmission (Meeusen et al., 2007), expression of brain-derived neurotrophic factors (Duman and Monteggia, 2006), and/or control of cerebral blood flow by the autonomic nervous system (Thayer et al., 2009). Moreover, central fatigue is associated with disturbances in perception, coordination and concentration (Lehmann et al., 1993). In the current study however, despite increases in peripheral and central fatigue evidenced through a reduction in physical performance, physical and mental energy, alertness and recovery state in addition to increased ratings of physical and mental fatigue, no evidence was observed for an effect of IT on cognitive processing.

As previously stated, confidence that the training volume and load were high enough is provided by similarity of training loads (Coutts et al., 2007) and resultant performance decrements (Halson et al., 2002) with other studies. Furthermore, cognitive tasks similar to those used in previous studies were used in the current study and thus differences in cognitive task is unlikely to account for our reported results. A main methodological difference between the current study and previous reports is the inclusion of a NT control group in addition to strict control of potential confounding variables. To ensure any observed changes in cognitive function could be attributed to IT, control groups and control of potential confounding factors are imperative for robust study designs in addition to reliable and valid conclusions. The current study employed rigorous controls for confounding variables within the inclusion criteria and throughout the study, including controlling for; exercise prior to performance testing, the intake of stimulants, cycling experience, medicinal intake and recent head collisions alongside the employment of a matched control group for comparison. Interestingly, compared to similar studies that did include a control group (Le Meur et al., 2013, Nederhof et al., 2007, Rietjens et al., 2005), only Rietjens et al. (2005) found a difference in RT following IT and this was not a direct increase in RT, but rather a reduced improvement compared to the control group. A meta-analysis by Etnier et al. (1997) examining the effect of fitness on cognitive performance found that as experimental rigor decreased, effect size increased and thus, the true magnitude of effect of IT on cognitive performance may not be truly observed in studies failing to implement experimental rigor.

In the present study, significant group main effects were found for calm sleep, sleep efficiency and numbers of awakenings per hour, with all being lower in the IT group throughout the study period with no differences at baseline. Although caution must be taken when interpreting main effects with no interaction, it is surprising that the perceptions of reduced sleep did not have an impact on cognitive function considering

the large amount of literature evidencing detrimental effects of sleep disturbance on cognition (Durmer and Dinges, 2005, Fullagar et al., 2015a, Fullagar et al., 2015b, Killgore, 2010). Sleep deprivation studies in athletes have reported slower and less accurate cognitive performance (Fullagar et al., 2015b) with increased errors, impaired decision making and increased fatigue (Reilly and Edwards, 2007). Furthermore, it has also been proposed that strenuous exercise in particular may be disruptive to sleep by causing decreased rapid eye movement sleep and increasing wakefulness (Driver and Taylor, 2000). Evidence of reduced sleep quality in an IT paradigm has also been reported, with 9-days of IT causing a significant and progressive decline in sleep quality (Killer et al., 2017).

It could be suggested that the cognitive measures used were not sensitive enough to detect an effect as they have not been used in this paradigm before. This is unlikely however as the tests used have been demonstrated to be sensitive to the effects of nutrition (Haskell et al., 2010, Haskell-Ramsay et al., 2018, Kennedy et al., 2017, Wightman et al., 2015), which are expected to be more subtle to detect than sleep impairment and IT. Surprisingly this is the only study the authors are aware of that examines sleep and cognitive performance throughout an IT period and thus further studies are warranted to determine the interaction between sleep and cognition in this paradigm. Furthermore, more research surrounding the conservation of good sleep during periods of IT is required; this will be particularly useful to athletes performing in congested training and tournament fixtures.

In support of our second hypothesis, large disturbances in psychological measures were observed following IT. These results are in line with previous observations that IT and HIE cause reductions in mood, leading to a negative psychological state (Comotto et al., 2015, Peluso and Andrade, 2005). The present study found a 57 % and 63 % increase in TMD following 7 and 14 days of IT respectively, in addition to significant increases in the specific subscales fatigue, vigour and confusion. This increase is markedly higher than the 28 % increase following two-weeks of IT reported by Halson et al. (2002) and 37 % increase following one-week of IT reported by Piacentini et al. (2016). Further psychological disturbance following both IT weeks included reductions in alertness, contentedness, physical energy, mental energy and total recovery as well as increases in physical fatigue, mental fatigue, total stress and significant disturbance in the recovery-stress balance in the IT group. The reduction in physical performance taken together with the changes in mood and recovery-stress balance suggest significant fatigue was induced after only 7 days. In the following

week, further reductions were observed, exacerbating the magnitude of fatigue within the IT group.

It has previously been suggested that a two-week taper period consisting of a 41-60% reduction in training volume is the most efficient strategy to optimise performance gains (Bosquet et al., 2007) for a supercompensation effect (Meeusen et al., 2013). During the current study however, no difference was found between TT performance at baseline and following the two-week taper period in the IT group. These results are similar to those of Halson et al. (2002) and may suggest the length of the taper for the IT group was not sufficient to show full recovery. This is unlikely however, as subjective responses were found to be superior to baseline at the end of the taper, with benefits observed for measures of stress, recovery, physical energy and aspects of mood including alertness and calmness. Interestingly, this may suggest that the benefits of IT are more psychological than physical, which has important implications for athletes and coaches who incorporate IT with the expectation of performance enhancement for competition.

The mood results are in support of previous reports that mood disturbances are dose-dependent in a progressive manner with increments in training load (Filaire et al., 2004), where reductions in training load are accompanied by either improved mood state or return to baseline (Coutts et al., 2007, Morgan et al., 1987). Though the behavioural effects of IT on mood appear to be well characterised, less is known on the neurophysiological mechanisms of mood disturbance. It is suggested however, that excessive exercise contributes to negative mood states due to modifications in opioid receptor activity (Saanijoki et al., 2018) and brain noradrenaline concentration, which is considered a major modulator of brain neural activity and a regulator of mood and motivation (Filaire et al., 2004).

5.5 Practical applications

The current study highlights the importance of scientific rigor for useful and practical recommendations. In contrast to previous studies, the cognitive results show no deterioration in performance across an IT period, though it is important that these results are considered within the context of the cognitive domains assessed. Whilst these results encourage future research to assess other cognitive processes, there are many practical applications that can be derived. The maintenance of sleep quality in addition to the adequate calorie intake, as demonstrate by no change in body mass,

likely contributed to the maintenance cognitive performance throughout the training period and thus highlights the importance of both sleep and nutrition for cognitive performance. Indeed, previous research examining cognitive recovery strategies suggest interventions that aim to restore fuel, such as nutritional strategies, as well as sleep are likely to have the largest effect. Currently however, there is little known on the effect size of any particular recovery strategy on the brain and its role in subsequent performance (Rattray et al., 2015). The failure to observe any benefit on IT to sporting performance questions the true benefit of IT and suggests that there may be more to be gained psychologically than physically. As demonstrated in Figure 5.6 however, there are clear individual responses to training paradigms and thus one of the greatest practical applications this study highlights is the need for individual evaluation with regards to training techniques, interventions and performance.

5.6 Limitations

A benefit of the current study is the ecological validity of the training regimen participants underwent; however, this strength of the study also presents itself as a limitation as the training sessions could not be controlled. To overcome this, participants completed an online training log (appendix F) which could be viewed by both the participant and the investigator; with extensive monitoring the investigator was able to remind participants how many hours they had left to complete to avoid them falling short. A second limitation of this study was the reliance on a fitness watch and HR monitor to capture training duration and intensity. As with many wearable technology devices, issues arose regarding loss of battery power. When this occurred (two occasions), data from similar sessions was used to account for the missing data as best as possible, though it is appreciated that this is not ideal. A further caveat that must also be acknowledged is the self-report nature of the subjective sleep assessment. To ensure accurate results, participants were required to complete the sleep diaries within 30-minutes of awakening whilst at home. As with any data collected away from the laboratory however, confidence cannot be given regarding the time at which subjective sleep measures were completed.

5.7 Conclusion & perspectives

Two-weeks of increased training volume successfully induced fatigue and caused significant performance decrements in trained male endurance cyclists. It was

hypothesised that an increase in training volume over a two-week period would impair cognitive function; this hypothesis was rejected however. It was found that when assessed in a rested state following two-weeks of IT, cognitive processes including RT, information processing, VSM and executive function were unaffected, despite significant increases in physical and mental fatigue. The effect of sleep on cognitive performance following IT remains unclear and requires further investigation. In agreement with our second hypothesis, impairment to psychological measures was observed during IT. Interestingly when compared to baseline, a two-week taper had beneficial effects on parameters of mood, energy, recovery and stress while no beneficial effects on physical performance were observed. Together these results suggest greater benefits of IT on psychological state than physical performance. These findings have implications for coaches and athletes who deliberately induce states of fatigue through IT as part of the normal training process, and suggest consideration over the purpose, desired outcomes and necessity of IT on an individual basis.

This chapter addressed the final aim of this thesis, to `*Characterise the effect of an intensified training intervention on cognitive performance, mood, energy and fatigue*`. No changes in cognitive performance were observed during or following two intense weeks of significantly increased training volume, despite clear reductions in physical performance. Whilst these findings are discussed within the chapter, it is perhaps of greater interest that this study found superior effects on psychological state than on physical performance following a two-week taper period. This study highlights the importance of individual responses to IT and proposes that the greatest advantages to performance may be in psychological preparation. In terms of application, this study provides interesting findings for athletes and applied practitioners of many sports who frequently undergo IT camps, and promotes consideration of the desired IT outcomes prior to implementation. The ease of administration and portability of both cognitive and mood assessment make it a viable prospect for future research to further increase the ecological validity of this work by assessing similar parameters during training camps and competition.

Chapter 6: General discussion

6.1 Experimental chapter synopsis

Exercise is a powerful stimulus, both physiologically and cognitively. Though still in its infancy, research examining the exercise-cognition interaction is growing, with advances in technology enabling a greater insight into behavioural effects and mechanisms of action. Previous research has mostly focussed on ageing populations in an effort to alleviate cognitive decline; young populations in an effort to promote cognitive development; and diseased populations in an effort to reduce negative symptoms. In comparison, healthy adult populations have received much less attention, particularly trained individuals who engage in regular exercise. The studies within this thesis aimed to contribute to, and build upon, existing knowledge by investigating cognitive performance and mood following different HIE paradigms in trained healthy populations (for study synopsis schematic see Figure 6.1).

The first study in this thesis (Chapter 2) attempted to identify and evaluate the current understanding within the area by systematically investigating existing literature. A review of this nature, assessing the effect of several combined moderators on the exercise cognition interaction, is needed as highlighted in a previous meta-analysis, due to their inherent limitations (Chang et al., 2012). As has been discussed throughout this thesis, multiple moderators influence the exercise-cognition interaction and thus Chapter 2 aimed to conduct a specific examination on the cognitive effects of acute HIE in trained populations. Following systematic review of seven databases, only 9 studies met the eligibility criteria to be included, which in itself highlighted the need for greater research within the area. Examination of the 9 studies revealed that information processing was the most examined cognitive domain, with 18 outcome measures of which 2 were positive, 15 were negligible and 1 was negative. Moreover, there appeared to be no effect of acute HIE on simple cognitive processes in trained individuals. The consensus behind higher-order processes however was unclear, with there being similar support for both negligible and detrimental effects, in addition to a greater variety of cognitive assessments used. The results of this section identified a gap in the literature and emphasised the need to assess a variety of cognitive domains.

The limited research identified in Chapter 2 supported the structure of the subsequent three experimental studies. The literature review reported an average time of previous HIE research protocols of 5.6 minutes. This was due to most of the protocols using continuous exercise models where exercise intensity is fixed. Most sports however, are of greater durations, often involve intermittent bursts of energy and in many

situations involve stress to the muscular and cardiovascular system. Due to this, the first experimental investigation (Chapter 3) aimed to identify the effects of prolonged strenuous exercise on cognitive performance and mood in trained male cyclists. This study used an exercise model that has previously been shown to induce both metabolic and mechanical stress. Supporting the results of the systematic review, there was no effect reported on simple reaction time (SRT) or four-choice reaction time (FCRT) but there was a negative effect on speed of information processing (Stroop task congruent stimuli), indicating an impairment in selective attention. Furthermore, prolonged strenuous exercise had detrimental effects on mood, with reductions in alertness and contentedness alongside increases in both physical and mental fatigue. The findings from this chapter add to the limited literature investigating HIE and indicate deleterious effects on cognition and mood in trained individuals that are accustomed to this type of exercise. In addition, this chapter also identified the ability of physical work to cause an increase in mental fatigue; a concept to date that has not been explored much in this context.

Chapter 4 was designed to extend upon the findings of Chapter 3 by exploring prolonged HIE within a different paradigm. In many sports, athletes are regularly exposed to consecutive days of competition and training. Recently, congested tournament fixtures have become a hot topic within the literature (Coutts, 2016), with concerns over insufficient recovery time being a catalyst for increased injury rates (Williams et al., 2017). The focus of this literature has predominantly surrounded physiological recovery, with little acknowledgement towards the impact that congested exercise may have on cognitive performance. Much of the previous literature has focussed on cognition during or following acute exercise (Lemmink and Visscher, 2005, McMorris and Rayment, 2007, Tsukamoto et al., 2016a), but the cumulative effects of multiple acute HIE bouts has rarely been explored and therefore this study aimed to address this gap. The results of Chapter 4 demonstrated a deterioration in cognitive performance across day 2 compared to day 1 in trained rugby players (familiar with both the type of exercise performed and congested fixture tournaments). Specifically, reductions in accuracy on the Stroop task assessing executive function were observed, alongside a slowing of RT on the FCRT task; furthermore, VSM following each exercise bout was worse as each day progressed. These reductions hold particular meaning when considered in a sporting context, with reductions having both performance and injury considerations. The mood results mirrored the cognitive findings, with significant reductions in alertness, contentedness, physical energy and mental energy, and increases in physical and

mental fatigue on day 2 compared to day 1. Furthermore, reductions in mood also occurred over time, getting worse from the first to the last exercise session. This is the first study to consider the effect of congested tournament fixtures on cognitive performance and mood and presents important considerations for any individual, sport and occupation that participate in repeated physical activity/exercise.

Extending on the findings from the first two empirical studies, the final study within this thesis (Chapter 5) was designed to investigate the effect of a two-week IT period on cognitive performance and mood alongside perceived sleep, physical performance and various physiological markers. Often in the form of training camps, many athletes incorporate high training volumes and limited recovery periods into their training regimen, with the intention of inducing a temporary reduction in physical performance after IT followed by a supercompensation effect after an adequate period of recovery (Meeusen et al., 2013). The purpose of this study was to explore the effects of IT on cognitive performance and mood throughout the training period. Results of Chapters 3 and 4 alongside previous literature led to the hypothesis that IT would cause significant reductions in cognitive performance alongside disturbances in mood. Despite this, the results reported in Chapter 5 provided no indication of a disturbance in cognitive function following a significant increase in training load. Conversely, significant mood, stress and recovery disturbances were observed during both IT weeks; this was followed by either a return to baseline or superior mood state after a two-week taper period. Reductions in physical performance were also observed, though there was a failure to see a super-compensatory effect of IT on performance markers. These results provide several points for discussion and add interesting debate to the literature. Namely, the results suggest that IT may provide greater psychological benefits over physiological benefits, whilst also proposing that in well-trained cyclist's cognitive performance, within the domains considered, is not affected when assessed in a rested state. The results also highlight the importance of subjective performance markers, which may be more sensitive to change and can provide equally as important information as objective markers. As ever, further studies are required to confirm these findings.

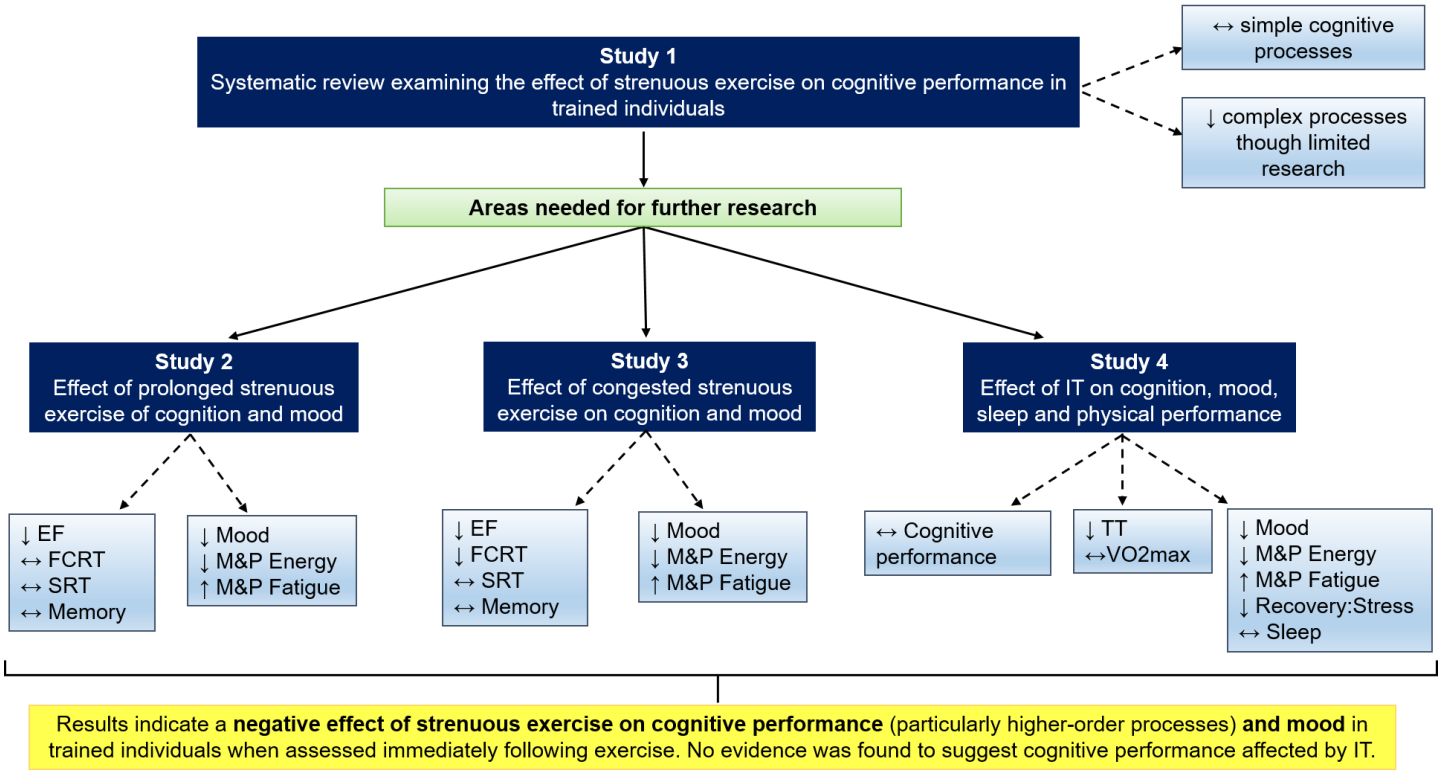

Figure 6.1 Schematic representation of the main findings of this thesis. Study 1 identified a gap in the literature, which was addressed in the subsequent 3 chapters. Following prolonged strenuous exercise, a reduction in executive function, namely selective attention and mood was observed in study 2. Study 3 reports reduced inhibitory control, FCRT and mood following a day of congested strenuous exercise. Lastly, study 4 found no change in cognitive performance despite reductions in mood and physical performance following two-weeks of IT. EF = executive function; SRT = simple reaction time; FCRT = four-choice reaction time; M & P = mental and physical; TT = time trial; $\dot{V}O_{2max}$ = maximum oxygen consumption; ↑ = increase; ↓ = decrease

6.2 Main Findings

The overall aim of this thesis was to investigate the effect of strenuous, high-intensity exercise on cognitive performance and mood in trained and athletic populations. A number of relevant issues have been discussed throughout each of the experimental chapters; the following section of this thesis aims to bring together the main findings in relation to the existing literature and provide further context and scope or application of the findings as well as discuss the limitations of the work and potential future areas of investigation.

6.2.1 Cognitive function and high-intensity exercise

There is an overwhelming amount of literature surrounding the effects of exercise on physical and mental processes. However, Chapter 2 identified a gap amongst this with minimal investigations examining the effects of HIE on cognitive performance in healthy trained populations. Indeed, trained sporting populations are an interesting population to examine for numerous reasons. As discussed in Chapter 1, chronic exercise is associated with several peripheral and central adaptations and participation in sport is believed to train cognitive abilities, with athletes being suggested to have superior cognitive abilities on fundamental laboratory cognitive tasks (Voss et al., 2009). Theoretically, it is tenable to suggest that trained sporting populations may be more resistant to exercise-induced fatigue and hold cognitive prowess compared to less trained populations following fatiguing exercise. The research presented in Chapter 2 contributes the first systematic review, within this specific area, to the literature. In total, 9 studies were identified that had examined trained populations during or following HIE according to the eligibility criteria outlined. The results are in line with that of earlier reviews, identifying exercise to have differential effects on specific cognitive domains (Chang et al., 2012, Colcombe and Kramer, 2003, Etnier et al., 1997, Lambourne and Tomporowski, 2010, McMorris and Hale, 2012). Neuroimaging studies have attempted to elucidate the underlying neurobiological processes of these findings, illustrating different task-related connectivity patterns (Bressler and Menon, 2010). Indeed, this is not surprising since the brain consists of multiple complex network systems that are finely integrated across all brain regions (van den Heuvel and Sporns, 2013). The results associated with each of the cognitive domains assessed throughout the thesis are discussed individually in the following sections.

6.2.1.1 Executive function

The findings from the systematic review in Chapter 2 support previous reports that suggest the effects of exercise on executive function are the most ambiguous, but also the most sensitive to change (Chang et al., 2012, Colcombe and Kramer, 2003, Dietrich and Audiffren, 2011, Dietrich and Sparling, 2004, Wang et al., 2013). The findings of Chapter 3 and Chapter 4 support this, with exercise having a detrimental effect on Stroop task performance in both experimental studies. This aligns with electrophysiological evidence from Pontifex and Hillman (2007) who found that exercise not only selectively reduced inhibition, but also reduced the activation (i.e. reduced N2 amplitude), increased the inefficiency of attentional resource allocation (i.e. reduced P3 amplitude) and delayed the cognitive processing speed related to the inhibitory response and stimulus discrimination (i.e. slower N2 and P3 latency). These results are in agreement with the conclusions of Dietrich and Audiffren (2011), where the authors note that tasks involving complex, top-down, conscious and effortful characteristics (such as those required by the Stroop task), are impaired during exercise compared with processes involving simple, bottom-up, unconscious and automatic features. It has been suggested that higher fitness levels may alleviate these effects due to a greater oxygen-carrying capacity compensating for the negative effects of vigorous exercise (Wang et al., 2013); the results of the current thesis however do not support this, at least with regards to response inhibition. However, as the current thesis did not directly compare participants of different fitness levels, firm conclusions cannot be drawn and require further investigation.

The Stroop task is one of the most extensively used tasks for assessing the ability to inhibit habitual responses in addition to selective attention, cognitive flexibility and information processing speed (Chang and Etnier, 2009). Interestingly, deteriorations in performance were found within different components of the Stroop task in each chapter, with RT on the congruent trials impaired following prolonged HIE (Chapter 3) and a reduction in accuracy on incongruent trials deteriorating on day 2 following one day of congested HIE (Chapter 4). Though both are subdomains of executive function (Vandierendonck, 2014), performance on congruent trials of the Stroop task predominantly assesses selective attention, whilst incongruent trial performance assesses inhibition. Indeed, incongruent trials have additional attentional demands relative to congruent trials as the word identity conflicts with the word ink colour. Furthermore, Mead et al. (2002) identified differences in brain activation patterns between congruent and incongruent interference conditions, highlighting the different

demands of the task. The reasons behind the differences observed in Stroop task performance in this thesis cannot be determined; it can be hypothesised however that either the type of exercise, the duration of exercise or the type of athlete used in the study contributed to the observed differences.

One of the largest mechanistic theories within the acute exercise-cognition literature postulates that of all the cognitive domains, executive function will be the most affected by exercise (Dietrich 2003). Exercise is a highly demanding activity for the brain which requires substantial resources, involving areas such as the primary sensory cortex, primary and supplementary motor cortices and the anterior region of the cerebellum (Christensen et al., 2000). The transient hypofrontality theory (Dietrich, 2003), which has since been expanded into the reticular-activating hypothesis (Dietrich and Audiffren, 2011), postulates when overtaxed by strenuous exercise, there is a downregulation in brain areas irrelevant to the motor task from areas supporting the highest cognitive functions. The PFC, being the primary higher-order area of the brain, is the first region affected by the heavy metabolic burden of HIE. This impact on PFC function makes its computations less likely to be supported sufficiently in any subsequent decision making process. Exercise intensity and duration are key components of this theory, which maintains that the brain has a limited information processing capacity (Broadbent, 1958) due to global cerebral blood flow, global metabolism and global oxygen uptake to the brain remaining constant despite an increased demand (Ide and Secher, 2000). In combination with this, it is well-accepted that exercise increases arousal and catecholamine concentrations; this may have created neural noise (the unsystematic, inherent, electrical oscillations found in neural networks) (Sanders, 1983) during post-exercise cognitive assessment, which may explain the observed results in Chapters 3 and 4. It is important to emphasise openly that many of the theoretical models commonly used in current literature to explain post-exercise changes in cognitive function were designed specifically to account for the psychological effects during exercise. Given the lack of detailed data about the time it takes for the brain to resume pre-exercise status, there should be caution when using these frameworks to explain post-exercise changes in cognition.

The overall results of this thesis are in agreement with the literature that suggest executive measures, such as selective attention and response inhibition, are the most sensitive to homeostatic disruption. Following prolonged and congested strenuous exercise, detrimental effects to Stroop task performance were observed in trained participants familiar to the exercise bout and intensity. This has important implications

for individuals that engage in these types of exercise paradigms, highlighting the importance of athlete monitoring and player rotation for both well-being and performance reasons. As untrained counterparts were not used as comparators, the difference and/or size of effect differences between trained and untrained populations cannot be established. It may be hypothesised however, based on the cognitive benefits of chronic training that untrained counterparts would have had greater deterioration in cognitive performance.

6.2.1.2 Visual spatial memory

Throughout this thesis VSM was assessed as it is pertinent to sporting performance (Furley and Memmert, 2010a). Interestingly, significant changes in VSM were only observed in Chapter 4. Results revealed a reduction in performance post-exercise during sessions 2 and 3 that was not observed in the control condition. Span score was also significantly lower in the exercise condition when compared to the control when assessed pre- and post-session 2 and post-session 3. As memory is an overarching cognitive concept that consists of multiple subdomains, it is important to compare like with like to avoid confounding conclusions. Indeed, VSM is a part of the central executive system according to Baddeley and Hitch`s WM model (Baddeley and Hitch, 1974) and refers to the short-term storage of visual and spatial information (Baddeley, 2007). Performance on the Corsi blocks task has been linked to dorsolateral prefrontal cortices (Nemmi et al., 2013, Toepper et al., 2010) as well as the hippocampus – the brain region most commonly associated with memory tasks – (Burgess et al., 2002), and has been justified as a measure of WM (Berch et al., 1998, Vandierendonck et al., 2004). Thus, the detrimental effects of congested exercise on VSM performance may have been associated with the reductions observed in the Stroop task, which also relies on central executive WM processes (McMorris et al., 2011).

Despite the relevance of VSM in sporting situations, particularly ball sports (Furley and Memmert, 2010a), there are no intervention studies to our knowledge that have assessed the effect of acute strenuous exercise on this domain in trained individuals, and thus the empirical studies in this thesis add the first to the literature. Indeed, improved vocabulary learning has been observed following acute high-intensity running (2 x 3 minute sprints at increasing speed) (Winter et al., 2007) however this cannot be likened to VSM as they are separate cognitive constructs. In young adults, Stroth et al. (2009a) found three 30-minute running sessions per week for 6 weeks

had a significant positive effect on VSM; however this assesses the chronic rather than acute effect of exercise. The lack of studies investigating the effect of strenuous exercise in trained populations is surprising, especially as athletes have been shown to perform better than non-athletes on sport-specific tasks of spatial memory (Mann et al., 2007) which suggests this to be a cognitive skill that is important for sporting performance and thus requires further research.

6.2.1.3 Simple cognitive processes

The results of Chapter 2 highlighted a preference of previous studies to assess simple cognitive processes such as SRT and CRT. Though this is likely due to the limited number of studies within this specific area of cognitive research, this finding does coincide with criticism of the literature from over 15 years ago, with it being highlighted that the types of tasks used by researchers mainly assessed basic information processing skills (Etnier et al., 1997, Tomporowski, 2003). Nevertheless, analysis showed there to be minimal effects of acute HIE on tasks of simple processing in trained individuals.

Interestingly these results were consistent in the subsequent three empirical investigations, particularly regarding SRT. There are many potential explanations for this. First, the trained status of the participants being tested. Individuals that regularly engage in HIE become familiarised with the high physiological task constraints; this may reduce the attentional demands associated with the control of the movement, subsequently leaving simple processing unaffected (Brisswalter et al., 1997). This supports the argument that individuals accustomed to HIE may be more resistant to fatigue, which may explain the maintenance of performance on simple tasks following heavy exercise found within this thesis. Indeed, trained individuals that engage in sport have been found to have faster reaction times than non-trained individuals (Kaur et al., 2006). This improvement comes directly from exercise training affecting motor functions and indirectly through other modes of information processing, such as attention and response preparation (Arcelin et al., 1998). As there is a ceiling effect with SRT (e.g. where there is a limit as to the quickest feasible RT humanly possible when accounting for stimulus detection and efferent response), it is of greater difficulty to see a facilitation of RT with exercise in trained individuals due to already having a fast baseline. The issue with some SRT tasks, such as the one used throughout this body of work, is that the simple nature of the task, that is, it only requires a simple finger movement, does not enable total RT to be separated into RT and movement

time and thus no distinction can be made between CNS response and motor response. If this is to be more closely investigated, whole body tasks are perhaps more suitable.

The only significant finding in what can be considered as basic information processing throughout the thesis was observed in Chapter 4, where FCRT performance deteriorated on day 2 following one congested day of exercise. This was accompanied by a reduction in accuracy on the more complex Stroop incongruent task condition used to assess inhibition, a domain of executive function. This is the first empirical study to assess cognitive performance following multiple congested exercise bouts and thus the findings cannot be directly compared to previous literature. However, the results of slower RT and reduced accuracy do support studies reporting reductions in performance (Ronglan et al., 2006), with decreases in technical skill (Moreira et al., 2016) and associations with increased injury rates (Carling et al., 2016) across congested matches and tournaments. When it is considered that there is increasing interest in the ramifications of cumulative fatigue and congested match fixtures, it is surprising that this is the first study to consider cognitive function when it is widely appreciated as a fundamental part in successful sporting performance (Coutts, 2016, Walsh, 2014).

With particular relevance to Chapters 4 and 5, it is also important to consider that periods of high physical workloads and competition can have deleterious effects on sleep (Fullagar et al., 2015b, Juliff et al., 2015). As discussed within the thesis, subjective measures of sleep in Chapter 4 would have been a positive addition to the study design; as a learning of this, subjective sleep was assessed in Chapter 5. Based on previous findings of adverse effects of IT on sleep (Halson et al., 2014, Killer et al., 2017), detrimental effects on subjective sleep and cognitive performance were expected. Despite disturbances to sleep parameters however, cognitive function remained unaffected. To ensure the effects observed on all measures assessed in Chapter 5 were due to the effects of IT and not acute exercise, cognitive performance was assessed in a rested state following 24-hours abstinence from strenuous exercise. The assessment of chronic HIE compared to acute HIE highlights the main methodological difference between Chapter 5 and the previous two chapters, which may explain the difference in findings. Though cognitive function remained unchanged, it is clear that IT disrupted the recovery-stress balance which, alongside congested tournament fixtures, has important implications for performance, well-being and injury prevention (Brink et al., 2010, Kellmann, 2010).

Overall, the studies presented in this thesis suggest prolonged, congested and intensified strenuous exercise have minimal effects on simple cognitive processing tasks such as SRT and FCRT, in trained populations. These findings are in general agreement with the previous literature as identified in the systematic literature review conducted in Chapter 2.

6.2.2 Mood, high-intensity exercise and cognitive function

In accordance with the main aims of this thesis, mood was investigated within multiple exercise paradigms across Chapters 3, 4 and 5. There is presently few studies on mood following strenuous exercise in trained populations and thus the current thesis contributes needed data and builds upon previous understanding. This is particularly important following suggestions that there may be a critical threshold intensity for disturbances in mood (Raglin and Morgan, 1985, Reed and Ones, 2006) and that optimal exercise-induced mood benefits may be subject to large individual differences (Berger et al., 2016, Brümmer et al., 2011, Motl et al., 2000, Raedeke, 2007, Schneider et al., 2009). Indeed, the “exercise preference hypothesis” suggests that the relaxation effects of exercise are linked to an individual’s physical activity history and exercise preferences, where the ‘preferred’ mode and intensity of exercise is what an individual is most familiar with (Boutcher et al., 1997, Brümmer et al., 2011, Schneider et al., 2009). Accordingly, reports of mood effects following exercise in the general population may not be appropriately applied to individuals that participate in regular training and/or competitive sport. Previous work supports this, demonstrating an increase in positive affect in trained individuals following HIE, while untrained participants experienced a reduction in positive affect and an increase in negative affect during and after exercise (Boutcher et al., 1997).

The results of this thesis are contrary to these previous reports however, as Chapters 3, 4 and 5 demonstrate a negative effect of strenuous exercise on mood in trained populations. Within all of the empirical studies, the Bond-Lader mood scale was used to assess alertness, contentedness and calmness. The scale was completed immediately at the time of testing (pre- and post-exercise) in Chapters 3 and 4, and following each training week in Chapter 5. Interestingly, a consistent finding throughout the experimental chapters was significant reductions in alertness and contentedness. This suggests strenuous exercise and IT loads have negative effects on these two specific aspects of mood in trained populations, irrespective of exercise duration or mode. These results support the notion that strenuous exercise has

negative implications for mood despite trained status. Calmness on the other hand showed a less consistent response, with no effect observed in Chapter 3, a positive effect post-exercise in Chapter 4 and a negative effect in Chapter 5 following a 2-week taper. As this final observation in Chapter 5 was not observed in the control group, it is postulated that the reduction in calmness following the taper period may be due to an excitement or anxiousness for the forthcoming trial. In support of this, alertness was significantly greater at the same time point, showing an increased state of arousal.

The findings in this thesis regarding alertness are particularly interesting. Exercise of sufficient intensity significantly increases stimulation of the adrenergic system, causing large increases in hypothalamic-pituitary-adrenal axis hormones such as adrenocorticotropic hormone, which stimulates the adrenal release of cortisol (McMorris et al., 2016). This `stress` response stimulates adrenaline synthesis, connecting high-intensity exercise with an increase in alertness (Buono et al., 1986). Interestingly, Davranche and Audiffren (2004b) found low (20% W_{max}) and moderate (50% W_{max}) intensity exercise significantly increased alertness (also assessed by the Bond-Lader mood scale). In the present thesis however, reductions in alertness following strenuous exercise were reported throughout the experimental chapters. These results may be explained in part by the findings of significant disturbances to both mental energy and fatigue. Specifically, a novel finding that has been present throughout this thesis is a significant increase in mental fatigue following exercise, despite minimal demands on mental exertion. This finding adds new knowledge to the existing literature as mental fatigue is most commonly associated with prolonged cognitive activity, not physical activity (Lorist et al., 2005). Not only does this support the negative effects observed on mood following strenuous exercise, but it also highlights the high demand exercise has on the brain which presents important considerations for prolonged, congested and chronic training paradigms.

Until relatively recently, little was known about the effects of mental fatigue within a sporting context. Recent evidence however provides convincing evidence that mental fatigue has a detrimental impact on sports performance (Van Cutsem et al., 2017) including intermittent running (Smith et al., 2015), endurance performance (Martin et al., 2018) and skill acquisition (Smith et al., 2016b). Most studies have focused on the consequences of induced mental fatigue (via sustained cognitive task performance) on physical performance (Van Cutsem et al., 2017). The current work however suggests that strenuous physical exertion itself, both acutely and chronically, causes significant increases in mental fatigue, which may subsequently have a negative

effect on sports performance. When practically applying this work, it is important that mental fatigue and mood are monitored and strategies are in place to help alleviate potential performance decrements, particularly in competition scenarios.

Chapters 3 and 4 assessed mood, energy and fatigue ratings prior to and immediately following exercise. In a different study design, Chapter 5 assessed cognitive function and mood chronically over an IT period, that is, following intensified weeks of training. Interestingly, similar results were found in this paradigm. To assess weekly mood and recovery-stress balance, the POMS-65 and RESTQ-Sport were administered. In support of the acute mood, energy and fatigue results observed in previous chapters, significant deteriorations in TMD and energy index were found across both IT weeks alongside a significant negative recovery-stress balance. These results are in support of previous work (Halson et al., 2002, Killer et al., 2017, Piacentini et al., 2016) and reiterate the negative effect of high training loads on mood, energy and fatigue as well as perceived recovery-stress balance.

In summary, the experimental chapters within this thesis indicate that there is a negative effect of strenuous exercise on mood and ratings of mental and physical energy and fatigue in trained individuals. The subjective markers used throughout this study have been consistent in finding reductions, particularly in alertness, contentedness and mental and physical energy alongside increases in mental and physical fatigue. These findings hold great value for sports performers and coaches as mood responses have been found to predict athletic performance (Beedie et al., 2000). As the maintenance of a functional mood profile when training and competing in strenuous and/or stressful conditions can underpin success, it is important to teach athletes strategies to regulate mood states that may threaten performance (Terry, 1995). In agreement with the conclusions of Saw et al. (2015), the work in this thesis supports the use of subjective measures to monitor change in well-being in response to exercise and training. Considering the results of the final empirical chapter, subjective ratings may be more sensitive and indicative of performance than objective measures, but this finding needs to be further validated. For now, practitioners could be advised to implement subjective measures of well-being and mood within a mixed methods approach to gain a holistic perspective of their athlete's performance.

6.3 Practical applications

The current thesis has examined and contributed new knowledge to the area surrounding strenuous exercise paradigms on cognitive performance, mood, energy and fatigue states in trained sporting individuals. Specifically, Chapters 3, 4 and 5 investigated the effect of prolonged, congested and intensified exercise respectively and practical implications specific to each of these paradigms are discussed in the respective chapters. All together, the evidence presented in this thesis suggests there to be negative effect of strenuous exercise on executive processes in trained sporting individuals and highlights the need for cognitive recovery strategies to be implemented in a similar fashion and with equal importance as are physiological and nutritional recovery strategies.

With increasing research investigating the interaction between exercise and cognition, it is well-established that cognitive function is fundamental to sporting success, yet there is still little knowledge on effective recovery strategies and ways to implement them. In a recent review examining central mechanisms for post-exertional recovery strategies and performance, Rattray et al. (2015) suggest interventions that aim to restore fuel, such a nutritional strategies, and sleep are likely to have the largest effect on the brain. The appreciation and understanding for cognitive recovery strategies that has been developed over recent years has opened up a new and promising area for future research, especially considering that there is currently little known on the effect size of any particular recovery strategy on the brain and its role in subsequent performance. Reference to psychological literature demonstrates well-known and effective mental recovery strategies including muscle relaxation, listening to calming music, systematic breathing and ‘power naps’ (Kellmann et al., 2018). More recently, an emerging cognitive recovery strategy for sports performance, as well as many other aspects of life, is that of meditation. In a recent study, Colzato and Kibele (2017) discuss how different types of meditation can enhance athletic performance, helping to actively control cognitive processes and emotions.

There is currently a need for strategies both during and following strenuous exercise to elicit and maintain optimal cognitive performance for sporting success. Whilst emphasising the importance of cognitive function and mood to sport performance, the current thesis highlights the negative effect heavy physiological load can have on cognitive processes and mood and suggests new avenues of research to practically benefit sports performance and athlete well-being.

6.4 Limitations of findings

A number of limitations exist in the interpretation of the findings from this thesis, which have been discussed in each chapter. The controls put in place allow for targeted analyses, however in most instances, this is at the expense of a degree of ecological validity. The following over-arching limitations are potential issues and criticisms of the work.

A pertinent issue when measuring cognitive function, particularly when wanting to make conclusions regarding sports performance, is the ability, or lack of ability, to accurately reflect cognitive behaviours that occur in a real-life environment. There is still a large question as to whether general laboratory tests of cognitive function, such as those used in this thesis, represent and transfer to performance in ecologically valid environments (Voss et al., 2009). Sport-specific cognitive tasks have been developed to try and address this issue by creating greater ecological validity. However, these tasks face similar limitations in that they are not validated to assess specific domains of cognitive function and similarly the transfer of performance to real-world environments is not currently known (Broadbent et al., 2015).

Alongside the cognitive tasks, the ecological validity of the exercise paradigms used is also a limitation within the first two experimental chapters. In Chapter 3, a protocol was selected that has been shown to significantly induce metabolic and mechanical stress (Bell et al., 2014). The purpose of this was to impose a known large stressor and examine the effects on cognitive performance. It is acknowledged however that, despite the cycling trial being validated against a cycle race, the ecological validity of the protocol in its entirety was low. An attempt was made in Chapter 4 to enhance the ecological validity of the study protocol by using previously reported GPS data regarding average sprint distance and work to recovery ratio assessing the demands of rugby sevens (Suarez-Arrones et al., 2012). The lab based protocol used however does not incorporate the multi-directional change, skill and cognitive components associated with invasion sports (Russell et al., 2011), each of which may influence the cognitive and mood response. In taking into account the limitations of the previous studies, Chapter 5 did employ a protocol with greater ecological validity concerning the exercise prescribed.

A further limitation is recognised with the use of subjective measures. Mood is a complex paradigm and is influenced by a plethora of both internal and external

factors. Whilst it is possible to control the environment in which mood is measured, certainty can never be entirely provided that any observed fluctuations in mood are purely due to interventional effects. A second subjective measure, perceived sleep, was also assessed in Chapter 5 with participants being required to complete sleep diaries within 30-minutes of awakening whilst at home. As with any data collected away from the laboratory, confidence cannot be given regarding the time at which subjective sleep measures were completed.

The premise of exercise interventions makes it impossible to blind participants to the study intervention. To reduce bias, repeated measures designs were used in the first two studies and participants were randomly allocated into the control or intervention condition in Chapter 5, which implemented a matched pairs design. This however does not solve the problem of participant blinding to the intervention. It is possible therefore, that preconceived expectancies regarding cognitive and physical performances may have influenced subjective responses.

The participant cohorts used in this series of studies also limits the application of the findings from this thesis. Only males were recruited and as such, the findings may not be applicable to females. Cognitive function and mood have been shown to fluctuate depending on menstrual cycle phase (Hampson, 1990, Symonds et al., 2004) and thus, for the purpose of control, only men were recruited throughout this series of work. More work is required in this area to gain a greater understanding behind the causes and effects of strenuous exercise on cognitive function and mood; particularly in women in which there is already limited research across many fields.

6.5 Future research and summary

The data from this thesis has provided an insight into the effect of strenuous exercise on cognitive performance and mood and has shown how this may be relevant and applied to various fields. Consequently, a number of potential avenues for future research have been identified. These include:

1. Chapter 2 highlighted that the mechanisms underpinning the effect of strenuous exercise on cognition and mood in humans are still not fully understood. Though the limitations of practicality are appreciated, greater research with neuroimaging technologies may provide a deeper insight into

the neurobiological underpinnings of disturbances to cognitive function and mood in both trained and untrained individuals.

2. Within the literature and throughout this thesis it is discussed that cardiovascular fitness may provide cognitive and mood benefits during exercise-induced stress. It is also apparent that expert athletes may have superior cognitive benefits, which are likely derived from years of practice within a particular domain. This opens discussion as to whether fitness level (e.g. $\dot{V}O_{2max}$) or sporting expertise (e.g. the direct interaction between the athlete and their environment of expertise) is more important in this relationship.

3. Chapter 3 used an exercise paradigm that caused both metabolic and mechanical stress. However, little research has investigated the effect of resistance exercise on cognitive function and mood despite its increasing popularity and importance for ageing populations. The limited information within this area alongside the important practical implications makes this a lucrative area for further work.

4. Most studies consider increased injury rates in congested tournament to be associated with increased physical demands. With considerations to the findings in Chapter 4 of reduced inhibitory control and FCRT, it would be interesting and meaningful to see if reductions in cognitive performance during congested tournaments were associated with increased injury rates.

5. Chapter 5 found no effect of IT on cognition. Indeed, the research within this area is ambiguous and requires further work in a greater variety of sports, whilst keeping individual responses at the forefront. This area would benefit from a comprehensive meta-analysis which would help researchers, coaches and athletes better understand the current state of research, and assist with the appropriate implementation of IT programs in training regimens.

6. The concept of individual critical thresholds in mood is intriguing both inside and outside of sport. This may help with exercise adherence and motivation, in addition to potential clinical applications.

7. Mental fatigue and sports performance is a relatively new concept within the sport and exercise literature. The observations within this thesis open new avenues for research within this area. These include investigations into the interactions between physical and mental fatigue and how these may affect individuals in both a sporting and occupational environment.

The aims of this thesis have been addressed and more importantly have contributed to the existing literature. While in the general population it is largely found that intense exercise has detrimental effects on cognition, there are limited studies investigating the effects of strenuous exercise on cognitive performance and mood in trained populations. The current body of work found negative effects of prolonged and congested exercise on certain domains of cognitive function, mood, energy and fatigue states in trained sports persons when assessed immediately after exercise. Conversely there was no effect found during or following 2 weeks intensified training on any cognitive domain when assessed in a rested state though detrimental effects were observed on parameters of mood, energy, fatigue and recovery states as well as physical performance. The work of this thesis supports the aforementioned consensus and extends the scope of study on this topic to trained and athletic populations. The practical application of the present work was a key consideration throughout and unique application seems most fitting to high-intensity sports that involve prolonged, congested or IT paradigms. Undoubtedly, three studies are insufficient to irrefutably demonstrate evidence of any intervention, its effects and its optimal application. Nevertheless, the results from this thesis suggest there to be domain specific effects on cognitive function and mood following strenuous exercise and thus encourage monitoring strategies to be put in place to ensure athlete well-being and promote optimal performance.

References

Åkerstedt, T., Hume, K., Minors, D. & Waterhouse, J. 1994. The meaning of good sleep: a longitudinal study of polysomnography and subjective sleep quality. *Journal of Sleep Research,* 3**,** 152-158.

Aks, D. J. 1998. Influence of exercise on visual search: implications for mediating cognitive mechanisms. *Percept Mot Skills,* 87**,** 771-83.

Ali, A., O'donnell, J., Von Hurst, P., Foskett, A., Holland, S., Starck, C. & Rutherfurd-Markwick, K. 2016. Caffeine ingestion enhances perceptual responses during intermittent exercise in female team-game players. *Journal of sports sciences,* 34**,** 330-341.

Alvarez, J. A. & Emory, E. 2006. Executive function and the frontal lobes: a meta-analytic review. *Neuropsychology review,* 16**,** 17-42.

Alves, C. R., Tessaro, V. H., Teixeira, L. A., Murakava, K., Roschel, H., Gualano, B. & Takito, M. Y. 2014. Influence of acute high-intensity aerobic interval exercise bout on selective attention and short-term memory tasks. *Percept Mot Skills,* 118**,** 63-72.

Alves, H., Voss, M., Boot, W. R., Deslandes, A., Cossich, V., Inacio Salles, J. & Kramer, A. F. 2013. Perceptual-cognitive expertise in elite volleyball players. *Frontiers in psychology,* 4**,** 36.

Anderson, R. J. & Brice, S. 2011. The mood-enhancing benefits of exercise: Memory biases augment the effect. *Psychology of Sport and Exercise,* 12**,** 79-82.

Ando, S. 2016. Acute Exercise and Cognition: Effects of Cerebral Oxygenation and Blood Flow. *In:* MCMORRIS, T. (ed.) *inExercise-Cognition Interaction: Neuroscience Perspectives.*

Ando, S., Kimura, T., Hamada, T., Kokubu, M., Moritani, T. & Oda, S. 2005. Increase in reaction time for the peripheral visual field during exercise above the ventilatory threshold. *European journal of applied physiology,* 94**,** 461-467.

Ando, S., Kokubu, M., Yamada, Y. & Kimura, M. 2011. Does cerebral oxygenation affect cognitive function during exercise? *European journal of applied physiology,* 111**,** 1973-1982.

Angevaren, M., Aufdemkampe, G., Verhaar, H., Aleman, A. & Vanhees, L. 2008. Physical activity and enhanced fitness to improve cognitive function in older people without known cognitive impairment. *Cochrane Database Syst Rev,* 3.

Arcelin, R., Delignieres, D. & Brisswalter, J. 1998. Selective effects of physical exercise on choice reaction processes. *Percept Mot Skills,* 87**,** 175-85.

Aron, A. R., Robbins, T. W. & Poldrack, R. A. 2004. Inhibition and the right inferior frontal cortex. *Trends in cognitive sciences,* 8**,** 170-177.

Arts, F. & Kuipers, H. 1994. The relation between power output, oxygen uptake and heart rate in male athletes. *International journal of sports medicine,* 15**,** 228-231.

Asamoah, S., Siegler, J., Chang, D., Scholey, A., Yeung, A. & Cheema, B. S. 2013. Effect of Aerobic Training on Cognitive Function and Arterial Stiffness in Sedentary Young Adults: A Pilot Randomized Controlled Trial. *Physiology Journal,* 2013.

Ashby, F. G. & Isen, A. M. 1999. A neuropsychological theory of positive affect and its influence on cognition. *Psychological review,* 106**,** 529.

Audiffren, M., Tomporowski, P. D. & Zagrodnik, J. 2009. Acute aerobic exercise and information processing: modulation of executive control in a Random Number Generation task. *Acta psychologica,* 132**,** 85-95.

Austin, D. J., Gabbett, T. J. & Jenkins, D. G. 2013. Reliability and sensitivity of a repeated high-intensity exercise performance test for rugby league and rugby union. *The Journal of Strength & Conditioning Research,* 27**,** 1128-1135.

Babaei, P., Damirchi, A., Mehdipoor, M. & Tehrani, B. S. 2014. Long term habitual exercise is associated with lower resting level of serum BDNF. *Neuroscience letters,* 566**,** 304-308.

Baddeley, A. 2007. *Working memory, thought, and action*, OUP Oxford.

Baddeley, A. D. & Hitch, G. 1974. Working memory. *Psychology of learning and motivation.* Elsevier.

Bandelow, S., Maughan, R., Shirreffs, S., Ozgünen, K., Kurdak, S., Ersöz, G., Binnet, M. & Dvorak, J. 2010. The effects of exercise, heat, cooling and rehydration strategies on cognitive function in football players. *Scandinavian journal of medicine & science in sports,* 20**,** 148-160.

Bard, C. & Fleury, M. 1978. Influence of imposed metabolic fatigue on visual capacity components. *Percept Mot Skills,* 47**,** 1283-7.

Barnes, D. E., Yaffe, K., Satariano, W. A. & Tager, I. B. 2003. A longitudinal study of cardiorespiratory fitness and cognitive function in healthy older adults. *Journal of the American Geriatrics Society,* 51**,** 459-465.

Bartholomew, J. B. & Miller, B. M. 2002. Affective responses to an aerobic dance class: the impact of perceived performance. *Research Quarterly for Exercise and Sport,* 73**,** 301-309.

Bassett Jr, D. R. & Howley, E. T. 2000. Limiting factors for maximum oxygen uptake and determinants of endurance performance. *Medicine & Science in Sports & Exercise,* 32**,** 70.

Basso, J. C. & Suzuki, W. A. 2017. The effects of acute exercise on mood, cognition, neurophysiology, and neurochemical pathways: a review. *Brain Plasticity,* 2**,** 127-152.

Becker, L., Kutz, D. & Voelcker-Rehage, C. 2016. Exercise-induced changes in basal ganglia volume and their relation to cognitive performance.

Beedie, C. J., Terry, P. C. & Lane, A. M. 2000. The profile of mood states and athletic performance: Two meta-analyses. *Journal of applied sport psychology,* 12**,** 49-68.

Bell, P. G., Walshe, I. H., Davison, G. W., Stevenson, E. J. & Howatson, G. 2014. Recovery facilitation with Montmorency cherries following high-intensity, metabolically challenging exercise. *Applied Physiology, Nutrition, and Metabolism,* 40**,** 414-423.

Berch, D. B., Krikorian, R. & Huha, E. M. 1998. The Corsi block-tapping task: Methodological and theoretical considerations. *Brain and cognition,* 38**,** 317-338.

Berger, B. G. 1996. Psychological benefits of an active lifestyle: What we know and what we need to know. *Quest,* 48**,** 330-353.

Berger, B. G., Darby, L. A., Zhang, Y., Owen, D. R. & Tobar, D. A. 2016. Mood alteration after 15 minutes of preferred intensity exercise: Examining heart rate, perceived exertion, and enjoyment. *Journal of Sport Behavior,* 39**,** 3.

Berger, B. G. & Friedman, E. 1988. Comparison of jogging, the relaxation response, and group interaction for stress reduction. *Journal of Sport and Exercise Psychology,* 10**,** 431-447.

Berger, B. G. & Motl, R. W. 2000. Exercise and mood: A selective review and synthesis of research employing the profile of mood states. *Journal of Applied Sport Psychology,* 12**,** 69-92.

Berger, B. G., Motl, R. W., Butki, B. D., Martin, D. T., Wilkinson, J. G. & Owen, D. R. 1999. Mood and cycling performance in response to three weeks of high-intensity, short-duration overtraining, and a two-week taper. *The Sport Psychologist,* 13**,** 444-457.

Berger, B. G. & Owen, D. R. 1992. Mood alteration with yoga and swimming: aerobic exercise may not be necessary. *Perceptual and Motor skills,* 75**,** 1331-1343.

Berger, B. G., Prapavessis, H., Grove, J. R. & Butki, B. D. 1997. Relationship of swimming distance, expectancy, and performance to mood states of competitive athletes. *Perceptual and Motor Skills,* 84**,** 1199-1210.

Billat, V. L., Demarle, A., Slawinski, J., Paiva, M. & Koralsztein, J.-P. 2001. Physical and training characteristics of top-class marathon runners. *Medicine & Science in Sports & Exercise,* 33**,** 2089-2097.

Billinger, S. A., Vidoni, E. D., Morris, J. K., Thyfault, J. P. & Burns, J. M. 2017. Exercise test performance reveals evidence of the cardiorespiratory fitness hypothesis. *Journal of aging and physical activity,* 25**,** 240-246.

Blackman, J. D., Towle, V. L., Lewis, G. F., Spire, J.-P. & Polonsky, K. S. 1990. Hypoglycmic Thresholds for Cognitive Dysfunction in Humans. *Diabetes,* 39**,** 828-835.

Blanchard, C. M., Rodgers, W. M., Spence, J. C. & Courneya, K. S. 2001. Feeling state responses to acute exercise of high and low intensity. *Journal of Science and Medicine in Sport,* 4**,** 30-38.

Boecker, H., Sprenger, T., Spilker, M. E., Henriksen, G., Koppenhoefer, M., Wagner, K. J., Valet, M., Berthele, A. & Tolle, T. R. 2008. The runner's high: opioidergic mechanisms in the human brain. *Cerebral Cortex,* 18**,** 2523-2531.

Bond, A. & Lader, M. 1974. The use of analogue scales in rating subjective feelings. *British Journal of Medical Psychology,* 47**,** 211-218.

Borer, K. T. 2003. *Exercise endocrinology*, Human Kinetics.

Borg, G. 1998. *Borg's perceived exertion and pain scales*, Human kinetics.

Bosquet, L., Montpetit, J., Arvisais, D. & Mujika, I. 2007. Effects of tapering on performance: a meta-analysis. *Medicine and science in sports and exercise,* 39**,** 1358.

Boutcher, S. H. & Landers, D. M. 1988. The effects of vigorous exercise on anxiety, heart rate, and alpha activity of runners and nonrunners. *Psychophysiology,* 25**,** 696-702.

Boutcher, S. H., Mcauley, E. & Courneya, K. S. 1997. Positive and negative affective response of trained and untrained subjects during and after aerobic exercise. *Australian Journal of Psychology,* 49**,** 28-32.

Brellenthin, A. G., Crombie, K. M., Hillard, C. J. & Koltyn, K. F. 2017. Endocannabinoid and Mood Responses to Exercise in Adults with Varying Activity Levels. *Translational Journal of the American College of Sports Medicine,* 2**,** 138-145.

Bressler, S. L. & Menon, V. 2010. Large-scale brain networks in cognition: emerging methods and principles. *Trends in cognitive sciences,* 14**,** 277-290.

Brink, M. S., Visscher, C., Arends, S., Zwerver, J., Post, W. J. & Lemmink, K. A. 2010. Monitoring stress and recovery: new insights for the prevention of injuries and illnesses in elite youth soccer players. *British journal of sports medicine,* 44**,** 809-815.

Brisswalter, J., Arcelin, R., Audiffren, M. & Delignieres, D. 1997. Influence of physical exercise on simple reaction time: effect of physical fitness. *Perceptual and motor skills,* 85**,** 1019-1027.

Brisswalter, J., Collardeau, M. & René, A. 2002. Effects of acute physical exercise characteristics on cognitive performance. *Sports Medicine,* 32**,** 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. A. 1958. *Perception and communication,* New York, Pergamon.

Broadbent, D. P., Causer, J., Williams, A. M. & Ford, P. R. 2015. Perceptual-cognitive skill training and its transfer to expert performance in the field: Future research directions. *European Journal of Sport Science,* 15**,** 322-331.

Browne, S., Flynn, M., O'neill, B., Howatson, G., Bell, P. & Haskell, C. 2017. Effects of acute high-intensity exercise on cognitive performance in trained individuals: A systematic review.

Brümmer, V., Schneider, S., Abel, T., Vogt, T. & Strueder, H. K. 2011. Brain cortical activity is influenced by exercise mode and intensity. *Medicine and science in sports and exercise,* 43**,** 1863-1872.

Buono, M. J., Yeager, J. E. & Hodgdon, J. A. 1986. Plasma adrenocorticotropin and cortisol responses to brief high-intensity exercise in humans. *Journal of Applied Physiology,* 61**,** 1337-1339.

Burgess, N., Maguire, E. A. & O'keefe, J. 2002. The human hippocampus and spatial and episodic memory. *Neuron,* 35**,** 625-641.

Burnley, M., Vanhatalo, A. & Jones, A. M. 2012. Distinct profiles of neuromuscular fatigue during muscle contractions below and above the critical torque in humans. *Journal of applied physiology,* 113**,** 215-223.

Carling, C., Mccall, A., Le Gall, F. & Dupont, G. 2016. The impact of short periods of match congestion on injury risk and patterns in an elite football club. *British journal of sports medicine,* 50**,** 764-768.

Casanova, F., Garganta, J., Silva, G., Alves, A., Oliveira, J. & Williams, A. M. 2013. Effects of prolonged intermittent exercise on perceptual-cognitive processes. *Med Sci Sports Exerc,* 45**,** 1610-7.

Caspersen, C. J., Powell, K. E. & Christenson, G. M. 1985. Physical activity, exercise, and physical fitness: definitions and distinctions for health-related research. *Public health reports,* 100**,** 126.

Castelli, D. M., Hillman, C. H., Buck, S. M. & Erwin, H. E. 2007. Physical fitness and academic achievement in third-and fifth-grade students. *Journal of Sport and Exercise Psychology,* 29**,** 239-252.

Chaddock, L., Erickson, K. I., Prakash, R. S., Vanpatter, M., Voss, M. W., Pontifex, M. B., Raine, L. B., Hillman, C. H. & Kramer, A. F. 2010. Basal ganglia volume is associated with aerobic fitness in preadolescent children. *Developmental neuroscience,* 32**,** 249-256.

Chaddock, L., Neider, M. B., Voss, M. W., Gaspar, J. G. & Kramer, A. F. 2011. Do athletes excel at everyday tasks? *Medicine and science in sports and exercise,* 43**,** 1920.

Chan, K. L., Tong, K. Y. & Yip, S. P. 2008. Relationship of serum brain-derived neurotrophic factor (BDNF) and health-related lifestyle in healthy human subjects. *Neuroscience letters,* 447**,** 124-128.

Chang, Y.-K., Chi, L., Etnier, J. L., Wang, C.-C., Chu, C.-H. & Zhou, C. 2014. Effect of acute aerobic exercise on cognitive performance: Role of cardiovascular fitness. *Psychology of Sport and Exercise,* 15**,** 464-470.

Chang, Y.-K. & Etnier, J. L. 2009. Exploring the Dose-Response Relationship between Resistance Exercise Intensity and Cognitive Function. *Journal of Sport and Exercise Psychology,* 31**,** 640-656.

Chang, Y.-K., Labban, J., Gapin, J. & Etnier, J. L. 2012. The effects of acute exercise on cognitive performance: a meta-analysis. *Brain research,* 1453**,** 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 and Exercise Psychology,* 33**,** 847-865.

Chartoff, E. H. & Connery, H. S. 2014. It's MORe exciting than mu: crosstalk between mu opioid receptors and glutamatergic transmission in the mesolimbic dopamine system. *Frontiers in pharmacology,* 5**,** 116.

Chmura, J., Krysztofiak, H., Ziemba, A. W., Nazar, K. & Kaciuba-Uścilko, H. 1998. Psychomotor performance during prolonged exercise above and below the blood lactate threshold. *European Journal of Applied Physiology and Occupational Physiology,* 77**,** 77-80.

Chmura, J. & Nazar, K. 2010. Parallel changes in the onset of blood lactate accumulation (OBLA) and threshold of psychomotor performance deterioration during incremental exercise after training in athletes. *International Journal of Psychophysiology,* 75**,** 287-290.

Chmura, J., Nazar, K. & Kaciuba-Uścilko, H. 1994. Choice Reaction Time During Graded Exercise in Relation to Blood Lactate and Plasma Catecholamine Thresholds. *Int J Sports Med,* 15**,** 172-176.

Choi, P. Y., Van Horn, J. D., Picker, D. E. & Roberts, H. I. 1993. Mood changes in women after an aerobics class: A preliminary study. *Health Care for Women International,* 14**,** 167-177.

Chomitz, V. R., Slining, M. M., Mcgowan, R. J., Mitchell, S. E., Dawson, G. F. & Hacker, K. A. 2009. Is there a relationship between physical fitness and academic achievement? Positive results from public school children in the northeastern United States. *Journal of School Health,* 79**,** 30-37.

Christensen, L. O., Johannsen, P., Sinkjær, T., Petersen, N., Pyndt, H. & Nielsen, J. B. 2000. Cerebral activation during bicycle movements in man. *Experimental Brain Research,* 135**,** 66-72.

Cian, C., Koulmann, N., Barraud, P., Raphel, C., Jimenez, C. & Melin, B. 2000. Influences of variations in body hydration on cognitive function: Effect of hyperhydration, heat stress, and exercise-induced dehydration. *Journal of Psychophysiology,* 14**,** 29.

Cirulli, F., Berry, A., Chiarotti, F. & Alleva, E. 2004. Intrahippocampal administration of BDNF in adult rats affects short-term behavioral plasticity in the Morris water maze and performance in the elevated plus-maze. *Hippocampus,* 14**,** 802-807.

Clingman, J. M. & Hilliard, D. V. 1994. Anxiety reduction in competitive running as a function of success. *Journal of Sport Behavior,* 17**,** 120.

Coco, M., Di Corrado, D., Calogero, R. A., Perciavalle, V., Maci, T. & Perciavalle, V. 2009. Attentional processes and blood lactate levels. *Brain research,* 1302**,** 205-211.

Cohen, J. 1992. Statistical power analysis. *Current directions in psychological science,* 1**,** 98-101.

Colcombe, S. & Kramer, A. F. 2003. Fitness effects on the cognitive function of older adults: a meta-analytic study. *Psychological science,* 14**,** 125-130.

Colcombe, S. J., Erickson, K. I., Scalf, P. E., Kim, J. S., Prakash, R., Mcauley, E., Elavsky, S., Marquez, D. X., Hu, L. & Kramer, A. F. 2006. Aerobic exercise training increases brain volume in aging humans. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences,* 61**,** 1166-1170.

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**,** 679-689.

Colzato, L. S. & Kibele, A. 2017. How different types of meditation can enhance athletic performance depending on the specific sport skills. *Journal of Cognitive Enhancement,* 1**,** 122-126.

Comotto, S., Bottoni, A., Moci, E. & Piacentini, M. 2015. Analysis of session-RPE and profile of mood states during a triathlon training camp. *The Journal of sports medicine and physical fitness,* 55**,** 361-367.

Cooper, C. 1973. Anatomical and physiological mechanisms of arousal, with special reference to the effects of exercise. *Ergonomics,* 16**,** 601-609.

Corsi, P. 1972. Memory and the medial temporal region of the brain. *Unpublished doctoral dissertation), McGill University, Montreal, QB*.

Coutts, A., Wallace, L. & Slattery, K. 2007. Monitoring changes in performance, physiology, biochemistry, and psychology during overreaching and recovery in triathletes. *International journal of sports medicine,* 28**,** 125-134.

Coutts, A. J. 2016. Fatigue in football: it's not a brainless task! *Journal of sports sciences,* 34**,** 1296.

Covassin, T., Weiss, L., Powell, J. & Womack, C. 2007. Effects of a maximal exercise test on neurocognitive function. *British journal of sports medicine,* 41**,** 370-374.

Cox, R. H., Thomas, T. R. & Davis, J. E. 2001. POSITIVE AND NEGATIVE AFFECT ASSOCIATED WITH AN ACUTE BOUT OF AEROBIC EXERCISE. *Journal of Exercise Physiology online,* 4.

Craft, L. L. & Perna, F. M. 2004. The benefits of exercise for the clinically depressed. *Primary care companion to the Journal of clinical psychiatry,* 6**,** 104.

Csikszentmihalyi, M. 2014. Toward a psychology of optimal experience. *Flow and the foundations of positive psychology.* Springer.

Currell, K. & Jeukendrup, A. E. 2008. Validity, reliability and sensitivity of measures of sporting performance. *Sports medicine,* 38**,** 297-316.

Currie, J., Ramsbottom, R., Ludlow, H., Nevill, A. & Gilder, M. 2009. Cardio-respiratory fitness, habitual physical activity and serum brain derived neurotrophic factor (BDNF) in men and women. *Neuroscience letters,* 451**,** 152-155.

Daamen, M. & Raab, M. 2012. Psychological assessments in physical exercise. *Functional neuroimaging in exercise and sport sciences.* Springer.

Daley, A. J. & Maynard, I. W. 2003. Preferred exercise mode and affective responses in physically active adults. *Psychology of Sport and Exercise,* 4**,** 347-356.

Davenne, D. 2009. Sleep of athletes–problems and possible solutions. *Biological Rhythm Research,* 40**,** 45-52.

Davey, C. 1973. Physical exertion and mental performance. *Ergonomics,* 16**,** 595-599.

Davis, C. L. & Lambourne, K. 2009. Exercise and cognition in children. *In:* MCMORRIS, T., TOMPOROWSKI, P. & AUDIFFREN, M. (eds.) *Exercise and cognitive function*

John Wiley & Sons.

Davranche, K. & Audiffren, M. 2004a. Facilitating effects of exercise on information processing. *Journal of Sports Sciences,* 22**,** 419-428.

Davranche, K. & Audiffren, M. 2004b. Facilitating effects of exercise on information processing. *J Sports Sci,* 22**,** 419-28.

Davranche, K., Audiffren, M. & Denjean, A. 2006a. A distributional analysis of the effect of physical exercise on a choice reaction time task. *Journal of Sports Sciences,* 24**,** 323-329.

Davranche, K., Brisswalter, J. & Radel, R. 2015. Where are the limits of the effects of exercise intensity on cognitive control? *Journal of Sport and Health Science,* 4**,** 56-63.

Davranche, K., Burle, B., Audiffren, M. & Hasbroucq, T. 2005. Information processing during physical exercise: a chronometric and electromyographic study. *Exp Brain Res,* 165**,** 532-40.

Davranche, K., Burle, B., Audiffren, M. & Hasbroucq, T. 2006b. Physical exercise facilitates motor processes in simple reaction time performance: an electromyographic analysis. *Neuroscience letters,* 396**,** 54-56.

Davranche, K. & Mcmorris, T. 2009. Specific effects of acute moderate exercise on cognitive control. *Brain and cognition,* 69**,** 565-570.

De Diego Acosta, A., García, J.-C., Fernandez-Pastor, V., Peran, S., Ruiz, M. & Guirado, F. 2001. Influence of fitness on the integrated neuroendocrine response to aerobic exercise until exhaustion. *Journal of physiology and biochemistry,* 57**,** 313-320.

De Pauw, K., Roelands, B., Cheung, S. S., De Geus, B., Rietjens, G. & Meeusen, R. 2013. Guidelines to classify subject groups in sport-science research. *International journal of sports physiology and performance,* 8**,** 111-122.

De Vries, W. R., Bernards, N. T., De Rooij, M. H. & Koppeschaar, H. P. 2000. Dynamic exercise discloses different time-related responses in stress hormones. *Psychosomatic Medicine,* 62**,** 866-872.

Decroix, L., Piacentini, M. F., Rietjens, G. & Meeusen, R. 2016. Monitoring Physical and Cognitive Overload During a Training Camp in Professional Female Cyclists. *International journal of sports physiology and performance*.

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 and Exercise Psychology,* 32**,** 312-323.

Del Percio, C., Babiloni, C., Infarinato, F., Marzano, N., Iacoboni, M., Lizio, R., Aschieri, P., Ce, E., Rampichini, S., Fano, G., Veicsteinas, A. & Eusebi, F. 2009. Effects of tiredness on visuo-spatial attention processes in elite karate athletes and non-athletes. *Arch Ital Biol,* 147**,** 1-10.

Delignières, D., Brisswalter, J. & Legros, P. 1994. Influence of physical exercise on choice reaction time in sports experts: the mediating role of resource allocation. *Journal of Human Movement Studies,* 27**,** 173-188.

Dietrich, A. 2003. Functional neuroanatomy of altered states of consciousness: the transient hypofrontality hypothesis. *Consciousness and cognition,* 12**,** 231-256.

Dietrich, A. 2006. Transient hypofrontality as a mechanism for the psychological effects of exercise. *Psychiatry research,* 145**,** 79-83.

Dietrich, A. 2009. The transient hypofrontality theory and its implications for emotion and cognition. *Exercise and cognitive function***,** 69-90.

Dietrich, A. & Audiffren, M. 2011. The reticular-activating hypofrontality (RAH) model of acute exercise. *Neuroscience & Biobehavioral Reviews,* 35**,** 1305-1325.

Dietrich, A. & Mcdaniel, W. F. 2004. Endocannabinoids and exercise. *British Journal of Sports Medicine,* 38**,** 536-541.

Dietrich, A. & Sparling, P. B. 2004. Endurance exercise selectively impairs prefrontal-dependent cognition. *Brain and Cognition,* 55**,** 516-524.

Dishman, R. K. & O'connor, P. J. 2009. Lessons in exercise neurobiology: the case of endorphins. *Mental Health and Physical Activity,* 2**,** 4-9.

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**,** 536-541.

Driver, H. S. & Taylor, S. R. 2000. Exercise and sleep. *Sleep medicine reviews,* 4**,** 387-402.

Drollette, E. S., Shishido, T., Pontifex, M. B. & Hillman, C. H. 2012. Maintenance of cognitive control during and after walking in preadolescent children. *Medicine & Science in Sports & Exercise,* 44**,** 2017-2024.

Dum, R. P. & Strick, P. L. 1991. The origin of corticospinal projections from the premotor areas in the frontal lobe. *Journal of Neuroscience,* 11**,** 667-689.

Duman, R. S. & Monteggia, L. M. 2006. A neurotrophic model for stress-related mood disorders. *Biological psychiatry,* 59**,** 1116-1127.

Dupuy, O., Billaut, F., Raymond, F., Benraiss, A., Theurot, D., Bosquet, L., Fraser, S. & Tremblay, J. 2018. Effect of acute intermittent exercise on cognitive flexibility: the role of exercise intensity. *Journal of Cognitive Enhancement,* 2**,** 146-156.

Dupuy, O., Renaud, M., Bherer, L. & Bosquet, L. 2010. Effect of functional overreaching on executive functions. *International journal of sports medicine,* 31**,** 617-623.

Durmer, J. S. & Dinges, D. F. Neurocognitive consequences of sleep deprivation. Seminars in neurology, 2005. Copyright© 2005 by Thieme Medical Publishers, Inc., 333 Seventh Avenue, New York, NY 10001, USA., 117-129.

Dustman, R. E., Ruhling, R. O., Russell, E. M., Shearer, D. E., Bonekat, H. W., Shigeoka, J. W., Wood, J. S. & Bradford, D. C. 1984. Aerobic exercise training and improved neuropsychological function of older individuals. *Neurobiology of aging,* 5**,** 35-42.

Eddens, L., Browne, S., Stevenson, E. J., Sanderson, B., Van Someren, K. & Howatson, G. 2017. The efficacy of protein supplementation during recovery from muscle-damaging concurrent exercise. *Applied Physiology, Nutrition, and Metabolism***,** 1-9.

Edwards, A. M., Macfadyen, A. & Clark, N. 2003. Test performance indicators from a single soccer specific fitness test differentiate between highly trained and recreationally active soccer players. *Journal of Sports Medicine and Physical Fitness,* 43**,** 14.

Ekkekakis, P., Hall, E. E., Vanlanduyt, L. M. & Petruzzello, S. J. 2000. Walking in (affective) circles: can short walks enhance affect? *Journal of Behavioral Medicine,* 23**,** 245-275.

Ekkekakis, P. & Petruzzello, S. J. 1999. Acute aerobic exercise and affect. *Sports Medicine,* 28**,** 337-347.

Elsworthy, N., Burke, D. & Dascombe, B. J. 2016. Physical and psychomotor performance of Australian football and rugby league officials during a match simulation. *J Sports Sci,* 34**,** 420-8.

Erickson, K. I., Banducci, S. E. & Akl, S. L. 2012. Relationship between exercise and cognitive processing studied by MRI in elderly people. *In:* BOECKER, H., HILLMAN, C. H., SCHEEF, L. & STRÜDER, H. K. (eds.) *Functional neuroimaging in exercise and sport sciences.* Springer Science & Business Media.

Erickson, K. I., Prakash, R. S., Voss, M. W., Chaddock, L., Hu, L., Morris, K. S., White, S. M., Wójcicki, T. R., Mcauley, E. & Kramer, A. F. 2009. Aerobic fitness is

associated with hippocampal volume in elderly humans. *Hippocampus,* 19**,** 1030-1039.

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 and Exercise Psychology,* 31**,** 469-483.

Etnier, J. L., Nowell, P. M., Landers, D. M. & Sibley, B. A. 2006. A meta-regression to examine the relationship between aerobic fitness and cognitive performance. *Brain research reviews,* 52**,** 119-130.

Etnier, J. L., Salazar, W., Landers, D. M., Petruzzello, S. J., Han, M. & Nowell, P. 1997. The Influence of Physical Fitness and Exercise Upon Cognitive Functioning: A Meta-Analysis. *Journal of sport & exercise psychology,* 19**,** 249-277.

Farrell, P. A., Gustafson, A. B., Morgan, W. P. & Pert, C. B. 1987. Enkephalins, catecholamines, and psychological mood alterations: effects of prolonged exercise. *Medicine & Science in Sports & Exercise*.

Faubert, J. 2013. Professional athletes have extraordinary skills for rapidly learning complex and neutral dynamic visual scenes. *Scientific reports,* 3**,** 1154.

Felts, W. & Vaccaro, P. 1988. The effect of aerobic exercise on post-exercise state anxiety and psychophysiological arousal as a function of fitness level. *Clin Kinesiol,* 42**,** 89-96.

Ferris, L. T., Williams, J. S. & Shen, C.-L. 2007. The effect of acute exercise on serum brain-derived neurotrophic factor levels and cognitive function. *Medicine and science in sports and exercise,* 39**,** 728-734.

Fery, Y. A., Ferry, A., Vom Hofe, A. & Rieu, M. 1997. Effect of physical exhaustion on cognitive functioning. *Percept Mot Skills,* 84**,** 291-8.

Filaire, E., Legrand, B., Lac, G. & Pequignot, J.-M. 2004. Training of elite cyclists: effects on mood state and selected hormonal responses. *Journal of sports sciences,* 22**,** 1025-1033.

Fiorenza, M., Hostrup, M., Gunnarsson, T. P., Shirai, Y., Schena, F., Iaia, F. M. & Bangsbo, J. 2019. Neuromuscular Fatigue and Metabolism during High-Intensity Intermittent Exercise. *Medicine and science in sports and exercise*.

Fleury, M. & Bard, C. 1987. Effects of different types of physical activity on the performance of perceptual tasks in peripheral and central vision and coincident timing. *Ergonomics,* 30**,** 945-958.

Fleury, M., Bard, C. & Carriere, L. 1981a. The effects of physical or perceptual work loads on a coincidence/anticipation task. *Percept Mot Skills,* 53**,** 843-50.

Fleury, M., Bard, C., Jobin, J. & Carrière, L. 1981b. Influence of different types of physical fatigue on a visual detection task. *Perceptual and Motor Skills*.

Foster, C. 1998. Monitoring training in athletes with reference to overtraining syndrome. *Medicine and science in sports and exercise,* 30**,** 1164-1168.

Fullagar, H. H., Duffield, R., Skorski, S., Coutts, A. J., Julian, R. & Meyer, T. 2015a. Sleep and recovery in team sport: current sleep-related issues facing professional team-sport athletes. *International journal of sports physiology and performance,* 10**,** 950-957.

Fullagar, H. H., Skorski, S., Duffield, R., Hammes, D., Coutts, A. J. & Meyer, T. 2015b. Sleep and athletic performance: the effects of sleep loss on exercise performance, and physiological and cognitive responses to exercise. *Sports medicine,* 45**,** 161-186.

Furley, P. & Memmert, D. 2010a. Differences in spatial working memory as a function of team sports expertise: the Corsi Block-tapping task in sport psychological assessment. *Perceptual and motor skills,* 110**,** 801-808.

Furley, P. A. & Memmert, D. 2010b. The role of working memory in sport. *International Review of Sport and Exercise Psychology,* 3**,** 171-194.

Fuss, J., Steinle, J., Bindila, L., Auer, M. K., Kirchherr, H., Lutz, B. & Gass, P. 2015. A runner's high depends on cannabinoid receptors in mice. *Proceedings of the National Academy of Sciences,* 112**,** 13105-13108.

Fuster, J. N. M. 2001. The prefrontal cortex—an update: time is of the essence. *Neuron,* 30**,** 319-333.

Gescheit, D. T., Cormack, S. J., Reid, M. & Duffield, R. 2015. Consecutive Days of Prolonged Tennis Match Play: Performance, Physical, and Perceptual Responses in Trained Players. *International Journal of Sports Physiology & Performance,* 10.

Gill, D., Williams, L. & Reifsteck, E. 2017. *Psychological dynamics of sport and exercise*, Human Kinetics.

Goldfarb, A. H. & Jamurtas, A. Z. 1997. β-Endorphin response to exercise. *Sports Medicine,* 24**,** 8-16.

Gould, D. & Krane, V. 1992. *The arousal–athletic performance relationship: Current status and future directions*, Human Kinetics Publishers.

Grego, F., Vallier, J.-M., Collardeau, M., Bermon, S., Ferrari, P., Candito, M., Bayer, P., Magnié, M.-N. & Brisswalter, J. 2004. Effects of long duration exercise on cognitive function, blood glucose, and counterregulatory hormones in male cyclists. *Neuroscience letters,* 364**,** 76-80.

Grego, F., Vallier, J.-M., Collardeau, M., Bermon, S., Rousseu, C., Cremieux, J. & Brisswalter, J. 2005. Influence of exercise duration and hydration status on cognitive function during prolonged cycling exercise. *International journal of sports medicine,* 26**,** 27-33.

Griffin, É. W., Mullally, S., Foley, C., Warmington, S. A., O'mara, S. M. & Kelly, Á. M. 2011. Aerobic exercise improves hippocampal function and increases BDNF in the serum of young adult males. *Physiology & behavior,* 104**,** 934-941.

Guizani, S., Bouzaouach, I., Tenenbaum, G., Ben Kheder, A., Feki, Y. & Bouaziz, M. 2006a. Simple and choice reaction times under varying levels of physical load in high skilled fencers. *J Sports Med Phys Fitness,* 46**,** 344-51.

Guizani, S. M., Bouzaouach, I., Tenenbaum, G., Ben Kheder, A., Feki, Y. & Bouaziz, M. 2006b. Simple and choice reaction times under varying levels of physical load in high skilled fencers. *Journal of Sports Medicine and Physical Fitness,* 46**,** 344-351.

Guizani, S. M., Tenenbaum, G., Bouzaouach, I., Ben Kheder, A., Feki, Y. & Bouaziz, M. 2006c. Information-processing under incremental levels of physical loads: comparing racquet to combat sports. *Journal of Sports Medicine and Physical Fitness,* 46**,** 335-343.

Gutin, B. 1966. Effect of increase in physical fitness on mental ability following physical and mental stress. *Research Quarterly. American Association for Health, Physical Education and Recreation,* 37**,** 211-220.

Gutin, B. & Di Gennaro, J. 1968. Effect of a treadmill run to exhaustion on performance of long addition. *Research Quarterly. American Association for Health, Physical Education and Recreation,* 39**,** 958-964.

Haggard, P. 2008. Human volition: towards a neuroscience of will. *Nature Reviews Neuroscience,* 9**,** 934.

Hall, E. E., Ekkekakis, P. & Petruzzello, S. J. 2002. The affective beneficence of vigorous exercise revisited. *British Journal of Health Psychology,* 7**,** 47-66.

Hall, E. E., Ekkekakis, P. & Petruzzello, S. J. 2007. Regional brain activity and strenuous exercise: predicting affective responses using EEG asymmetry. *Biological psychology,* 75**,** 194-200.

Halson, S. L. 2014. Monitoring training load to understand fatigue in athletes. *Sports Medicine,* 44**,** 139-147.

Halson, S. L., Bartram, J., West, N., Stephens, J., Argus, C. K., Driller, M. W., Sargent, C., Lastella, M., Hopkins, W. G. & Martin, D. T. 2014. Does hydrotherapy help or hinder adaptation to training in competitive cyclists. *Med Sci Sports Exerc,* 46**,** 1631-9.

Halson, S. L., Bridge, M. W., Meeusen, R., Busschaert, B., Gleeson, M., Jones, D. A. & Jeukendrup, A. E. 2002. Time course of performance changes and fatigue markers during intensified training in trained cyclists. *Journal of applied physiology,* 93**,** 947-956.

Hampson, E. 1990. Variations in sex-related cognitive abilities across the menstrual cycle. *Brain and cognition,* 14**,** 26-43.

Hancock, S. & Mcnaughton, L. 1986. Effects of fatigue on ability to process visual information by experienced orienteers. *Percept Mot Skills,* 62**,** 491-8.

Hansen, C. J., Stevens, L. C. & Coast, J. R. 2001. Exercise duration and mood state: How much is enough to feel better? *Health Psychology,* 20**,** 267.

Haskell-Ramsay, C. F., Jackson, P. A., Dodd, F. L., Forster, J. S., Bérubé, J., Levinton, C. & Kennedy, D. O. 2018. Acute Post-Prandial Cognitive Effects of Brown Seaweed Extract in Humans. *Nutrients,* 10**,** 85.

Haskell, C. F., Robertson, B., Jones, E., Forster, J., Jones, R., Wilde, A., Maggini, S. & Kennedy, D. O. 2010. Effects of a multi-vitamin/mineral supplement on cognitive function and fatigue during extended multi-tasking. *Human Psychopharmacology: Clinical and Experimental,* 25**,** 448-461.

Head, A., Kendall, M., Ferner, R. & Eagles, C. 1996. Acute effects of beta blockade and exercise on mood and anxiety. *British journal of sports medicine,* 30**,** 238-242.

Heijnen, S., Hommel, B., Kibele, A. & Colzato, L. S. 2016. Neuromodulation of aerobic exercise—a review. *Frontiers in psychology,* 6**,** 1890.

Higgins, J. P. T. & Green, S. 2011. *Cochrane Handbook for Systematic Reviews of Interventions 5.1.0 [updated March 2011].* The Cochrane Collaboration; 2011.

Higham, D. G., Pyne, D. B., Anson, J. M. & Eddy, A. 2012. Movement patterns in rugby sevens: effects of tournament level, fatigue and substitute players. *Journal of Science and Medicine in Sport,* 15**,** 277-282.

Hill, E., Zack, E., Battaglini, C., Viru, M., Viru, A. & Hackney, A. 2008. Exercise and circulating cortisol levels: the intensity threshold effect. *Journal of endocrinological investigation,* 31**,** 587-591.

Hillman, C. H., Erickson, K. I. & Kramer, A. F. 2008. Be smart, exercise your heart: exercise effects on brain and cognition. *Nature reviews neuroscience,* 9**,** 58-65.

Hillman, C. H., Snook, E. M. & Jerome, G. J. 2003. Acute cardiovascular exercise and executive control function. *International Journal of Psychophysiology,* 48**,** 307-314.

Hoffman, J. R., Landau, G., Stout, J. R., Dabora, M., Moran, D. S., Sharvit, N., Hoffman, M. W., Moshe, Y. B., Mccormack, W. P. & Hirschhorn, G. 2014. β-alanine supplementation improves tactical performance but not cognitive function in combat soldiers. *Journal of the International Society of Sports Nutrition,* 11**,** 1.

Hoffman, M. D. & Hoffman, D. R. 2008. Exercisers achieve greater acute exercise-induced mood enhancement than nonexercisers. *Archives of physical medicine and rehabilitation,* 89**,** 358-363.

Hogervorst, E., Riedel, W., Jeukendrup, A. & Jolles, J. 1996. Cognitive performance after strenuous physical exercise. *Perceptual and Motor Skills,* 83**,** 479-488.

Howatson, G. & Milak, A. 2009. Exercise-induced muscle damage following a bout of sport specific repeated sprints. *The Journal of Strength & Conditioning Research,* 23**,** 2419-2424.

Huang, T., Larsen, K., Ried-Larsen, M., Møller, N. & Andersen, L. B. 2014. The effects of physical activity and exercise on brain-derived neurotrophic factor in healthy humans: A review. *Scandinavian journal of medicine & science in sports,* 24**,** 1-10.

Hung, T.-M., Tsai, C.-L., Chen, F.-T., Wang, C.-C. & Chang, Y.-K. 2013. The immediate and sustained effects of acute exercise on planning aspect of executive function. *Psychology of Sport and Exercise,* 14**,** 728-736.

Hüttermann, S. & Memmert, D. 2014. Does the inverted-u function disappear in expert athletes? An analysis of the attentional behavior under physical exercise of athletes and non-athletes. *Physiology & Behavior,* 131**,** 87-92.

Hwang, J., Castelli, D. M. & Gonzalez-Lima, F. 2017. The positive cognitive impact of aerobic fitness is associated with peripheral inflammatory and brain-derived neurotrophic biomarkers in young adults. *Physiology & behavior,* 179**,** 75-89.

Ide, K. & Secher, N. H. 2000. Cerebral blood flow and metabolism during exercise. *Progress in neurobiology,* 61**,** 397-414.

Indovina, I. & Macaluso, E. 2004. Occipital–parietal interactions during shifts of exogenous visuospatial attention: trial-dependent changes of effective connectivity. *Magnetic resonance imaging,* 22**,** 1477-1486.

Jeukendrup, A., Hesselink, M., Snyder, A., Kuipers, H. & Keizer, H. 1992. Physiological changes in male competitive cyclists after two weeks of intensified training. *International journal of sports medicine,* 13**,** 534-541.

Johnston, R. D., Gabbett, T. J. & Jenkins, D. G. 2013. Influence of an intensified competition on fatigue and match performance in junior rugby league players. *Journal of Science and Medicine in Sport,* 16**,** 460-465.

Joyce, J., Graydon, J., Mcmorris, T. & Davranche, K. 2009. The time course effect of moderate intensity exercise on response execution and response inhibition. *Brain and cognition,* 71**,** 14-19.

Juliff, L. E., Halson, S. L. & Peiffer, J. J. 2015. Understanding sleep disturbance in athletes prior to important competitions. *Journal of Science and Medicine in Sport,* 18**,** 13-18.

Kahneman, D. 1973. *Attention and effort*, Prentice-Hall Englewood Cliffs, NJ.

Kamijo, K., Hayashi, Y., Sakai, T., Yahiro, T., Tanaka, K. & Nishihira, Y. 2009. Acute effects of aerobic exercise on cognitive function in older adults. *Journals of Gerontology: Series B,* 64**,** 356-363.

Kamijo, K., Nishihira, Y., Hatta, A., Kaneda, T., Kida, T., Higashiura, T. & Kuroiwa, K. 2004a. Changes in arousal level by differential exercise intensity. *Clin Neurophysiol,* 115**,** 2693-8.

Kamijo, K., Nishihira, Y., Hatta, A., Kaneda, T., Wasaka, T., Kida, T. & Kuroiwa, K. 2004b. Differential influences of exercise intensity on information processing in the central nervous system. *Eur J Appl Physiol,* 92**,** 305-11.

Kamijo, K., O'leary, K. C., Pontifex, M. B., Themanson, J. R. & Hillman, C. H. 2010. The relation of aerobic fitness to neuroelectric indices of cognitive and motor task preparation. *Psychophysiology,* 47**,** 814-821.

Kashihara, K., Maruyama, T., Murota, M. & Nakahara, Y. 2009. Positive effects of acute and moderate physical exercise on cognitive function. *Journal of physiological anthropology,* 28**,** 155-164.

Kashihara, K. & Nakahara, Y. 2005. Short-term effect of physical exercise at lactate threshold on choice reaction time. *Perceptual and motor skills,* 100**,** 275-291.

Kaur, P., Paul, M. & Sandhu, J. S. 2006. Auditory and visual reaction time in athletes, healthy controls, and patients of type 1 diabetes mellitus: A comparative study. *International Journal of Diabetes in Developing Countries,* 26**,** 112-115.

Kellmann, M. 2010. Preventing overtraining in athletes in high-intensity sports and stress/recovery monitoring. *Scandinavian journal of medicine & science in sports,* 20**,** 95-102.

Kellmann, M. & Kallus, K. W. 2001. *Recovery-stress questionnaire for athletes: User manual*, Human Kinetics.

Kellmann, M., Pelka, M. & Beckmann, J. 2018. Psychological relaxation techniques to enhance recovery in sports. *Sport, recovery and performance: Interdisciplinary insights***,** 247-259.

Kemppainen, J., Aalto, S., Fujimoto, T., Kalliokoski, K. K., Långsjö, J., Oikonen, V., Rinne, J., Nuutila, P. & Knuuti, J. 2005. High intensity exercise decreases global brain glucose uptake in humans. *The Journal of physiology,* 568**,** 323-332.

Kennedy, D. O., Jackson, P. A., Forster, J., Khan, J., Grothe, T., Perrinjaquet-Moccetti, T. & Haskell-Ramsay, C. F. 2017. Acute effects of a wild green-oat (Avena sativa) extract on cognitive function in middle-aged adults: A double-blind, placebo-controlled, within-subjects trial. *Nutritional neuroscience,* 20**,** 135-151.

Kessels, R. P., Van Den Berg, E., Ruis, C. & Brands, A. M. 2008. The backward span of the Corsi Block-Tapping Task and its association with the WAIS-III Digit Span. *Assessment,* 15**,** 426-434.

Killer, S. C., Svendsen, I. S., Jeukendrup, A. & Gleeson, M. 2017. Evidence of disturbed sleep and mood state in well-trained athletes during short-term intensified training with and without a high carbohydrate nutritional intervention. *Journal of sports sciences,* 35**,** 1402-1410.

Killgore, W. D. 2010. Effects of sleep deprivation on cognition. *Progress in brain research.* Elsevier.

Kmet, L. M., Lee, R. C. & Cook, L. S. 2004. Standard quality assessment criteria for evaluating primary research papers from a variety of fields. Alberta Heritage Foundation for Medical Research Edmonton.

Knaepen, K., Goekint, M., Heyman, E. M. & Meeusen, R. 2010. Neuroplasticity—exercise-induced response of peripheral brain-derived neurotrophic factor. *Sports Medicine,* 40**,** 765-801.

Knicker, A. J., Renshaw, I., Oldham, A. R. & Cairns, S. P. 2011. Interactive processes link the multiple symptoms of fatigue in sport competition. *Sports Medicine,* 41**,** 307-328.

Kramer, A. F. & Erickson, K. I. 2007. Effects of physical activity on cognition, well-being, and brain: Human interventions. *Alzheimer's & Dementia,* 3**,** S45-S51.

Labelle, V., Bosquet, L., Mekary, S. & Bherer, L. 2013. Decline in executive control during acute bouts of exercise as a function of exercise intensity and fitness level. *Brain and cognition,* 81**,** 10-17.

Labelle, V., Bosquet, L., Mekary, S., Vu, T. T. M., Smilovitch, M. & Bherer, L. 2014. Fitness level moderates executive control disruption during exercise regardless of age. *Journal of Sport and Exercise Psychology,* 36**,** 258-270.

Lambourne, K. & Tomporowski, P. 2010. The effect of exercise-induced arousal on cognitive task performance: A meta-regression analysis. *Brain Research,* 1341**,** 12-24.

Lane, A., Hewston, R., Redding, E. & Whyte, G. P. 2003. Mood changes following modern-dance classes. *Social Behavior and Personality: an international journal,* 31**,** 453-460.

Le Meur, Y., Hausswirth, C., Natta, F., Couturier, A., Bignet, F. & Vidal, P. P. 2013. A multidisciplinary approach to overreaching detection in endurance trained athletes. *J Appl Physiol (1985),* 114**,** 411-20.

Lee, J. K., Koh, A. C., Koh, S. X., Liu, G. J., Nio, A. Q. & Fan, P. W. 2014. Neck cooling and cognitive performance following exercise-induced hyperthermia. *European journal of applied physiology,* 114**,** 375-384.

Legaz-Arrese, A., Munguía-Izquierdo, D., Nuviala, A. N., Serveto-Galindo, O., Urdiales, D. M. & Masía, J. R. 2007. Average VO2max as a function of running performances on different distances. *Science & sports,* 22**,** 43-49.

Lehmann, M., Foster, C. & Keul, J. 1993. Overtraining in endurance athletes: a brief review. *Medicine & Science in Sports & Exercise*.

Lemmink, K. & Visscher, C. 2005. Effect of intermittent exercise on multiple-choice reaction times of soccer players. *Perceptual and motor skills,* 100**,** 85-95.

Lepers, R., Hausswirth, C., Maffiuletti, N., Brisswalter, J. & Van Hoecke, J. 2000. Evidence of neuromuscular fatigue after prolonged cycling exercise. *Medicine & Science in Sports & Exercise,* 32**,** 1880-1886.

Levitt, S. & Gutin, B. 1971. Multiple choice reaction time and movement time during physical exertion. *Res Q,* 42**,** 405-10.

Lezak, M. D. 2004. *Neuropsychological assessment*, Oxford University Press, USA.

Llorens, F., Sanabria, D. & Huertas, F. 2015. The influence of acute intense exercise on exogenous spatial attention depends on physical fitness level. *Experimental psychology*.

Lo Bue-Estes, C., Willer, B., Burton, H., Leddy, J. J., Wilding, G. E. & Horvath, P. J. 2008. Short-term exercise to exhaustion and its effects on cognitive function in young women. *Perceptual and motor skills,* 107**,** 933-945.

Lorist, M. M., Boksem, M. A. & Ridderinkhof, K. R. 2005. Impaired cognitive control and reduced cingulate activity during mental fatigue. *Cognitive Brain Research,* 24**,** 199-205.

Luft, C. D., Takase, E. & Darby, D. 2009. Heart rate variability and cognitive function: effects of physical effort. *Biological psychology,* 82**,** 164-168.

Magnie, M.-N., Bermon, S., Martin, F., Madany-Lounis, M., Suisse, G., Muhammad, W. & Dolisi, C. 2000. P300, N400, aerobic fitness, and maximal aerobic exercise. *Psychophysiology,* 37**,** 369-377.

Malomsoki, J. & Szmodis, I. 1970. Visual response time changes in athletes during physical effort. *Int Z Angew Physiol,* 29**,** 65-72.

Mann, D. T., Williams, A. M., Ward, P. & Janelle, C. M. 2007. Perceptual-cognitive expertise in sport: A meta-analysis. *Journal of Sport and Exercise Psychology,* 29**,** 457-478.

Maraki, M., Tsofliou, F., Pitsiladis, Y., Malkova, D., Mutrie, N. & Higgins, S. 2005. Acute effects of a single exercise class on appetite, energy intake and mood. Is there a time of day effect? *Appetite,* 45**,** 272-278.

Markoff, R. A., Ryan, P. & Young, T. 1982. Endorphins and mood changes in long-distance running. *Medicine and science in sports and exercise,* 14**,** 11-15.

Maroulakis, E. & Zervas, Y. 1993. Effects of aerobic exercise on mood of adult women. *Perceptual and motor skills,* 76**,** 795-801.

Martin, K., Meeusen, R., Thompson, K. G., Keegan, R. & Rattray, B. 2018. Mental Fatigue Impairs Endurance Performance: A Physiological Explanation. *Sports Medicine***,** 1-11.

Mcadam, R. E. & Wang, Y. K. 1967. Performance of a simple mental task following various treatments. *Research Quarterly. American Association for Health, Physical Education and Recreation,* 38**,** 208-212.

Mcgowan, R. W., Pierce, E. F. & Jordan, D. 1991. Mood alterations with a single bout of physical activity. *Perceptual and motor skills,* 72**,** 1203-1209.

Mcinman, A. D. & Berger, B. G. 1993. Self-concept and mood changes associated with aerobic dance. *Australian Journal of Psychology,* 45**,** 134-140.

Mcmorris, T. 2016. The history of research into the acute exercise-cognition interaction: A cognitive psychology approach. *In:* MCMORRIS, T. (ed.) *Exercise-cognition interaction.* London: Elsevier.

Mcmorris, T., Collard, K., Corbett, J., Dicks, M. & Swain, J. 2008. A test of the catecholamines hypothesis for an acute exercise–cognition interaction. *Pharmacology Biochemistry and Behavior,* 89**,** 106-115.

Mcmorris, T. & Corbett, J. 2016. Effects of athletic fitness on exercise-cognition interaction. *In:* MCMORRIS, T. (ed.) *Exercise-Cognition Interaction: Neuroscience Perspectives,.* London: Academix press.

Mcmorris, T., Davranche, K., Jones, G., Hall, B., Corbett, J. & Minter, C. 2009. Acute incremental exercise, performance of a central executive task, and sympathoadrenal system and hypothalamic-pituitary-adrenal axis activity. *International journal of psychophysiology,* 73**,** 334-340.

Mcmorris, T. & Graydon, J. 1996a. Effect of exercise on soccer decision-making tasks of differing complexities. *Journal of Human Movement Studies,* 30**,** 177-193.

Mcmorris, T. & Graydon, J. 1996b. The effect of exercise on the decision-making performance of experienced and inexperienced soccer players. *Research Quarterly for Exercise and Sport,* 67**,** 109-114.

Mcmorris, T. & Graydon, J. 1997a. The effect of exercise on cognitive performance in soccer-specific tests. *J Sports Sci,* 15**,** 459-68.

Mcmorris, T. & Graydon, J. 1997b. The effect of exercise on cognitive performance in soccer-specific tests. *Journal of Sports Sciences,* 15**,** 459-468.

Mcmorris, T. & Graydon, J. 2000. The effect of incremental exercise on cognitive performance. *International Journal of Sport Psychology,* 31**,** 66-81.

Mcmorris, T. & Hale, B. J. 2012. Differential effects of differing intensities of acute exercise on speed and accuracy of cognition: a meta-analytical investigation. *Brain and cognition,* 80**,** 338-351.

Mcmorris, T., Hale, B. J., Corbett, J., Robertson, K. & Hodgson, C. I. 2015. Does acute exercise affect the performance of whole-body, psychomotor skills in an inverted-U fashion? A meta-analytic investigation. *Physiology & behavior,* 141**,** 180-189.

Mcmorris, T. & Keen, P. 1994. Effect of exercise on simple reaction times of recreational athletes. *Percept Mot Skills,* 78**,** 123-30.

Mcmorris, T., Myers, S., Macgillivary, W. W., Sexsmith, J. R., Fallowfield, J., Graydon, J. & Forster, D. 1999. Exercise, plasma catecholamine concentrations and decision-making performance of soccer players on a soccer-specific test. *Journal of Sports Sciences,* 17**,** 667-676.

Mcmorris, T. & Rayment, T. 2007. Short-duration, high-intensity exercise and performance of a sports-specific skill: A preliminary study. *Perceptual and Motor Skills,* 105**,** 523-530.

Mcmorris, T., Sproule, J., Draper, S. & Child, R. 2000. Performance of a psychomotor skill following rest, exercise at the plasma epinephrine threshold and maximal intensity exercise. *Perceptual and Motor Skills,* 91**,** 553-562.

Mcmorris, T., Sproule, J., Turner, A. & Hale, B. J. 2011. Acute, intermediate intensity exercise, and speed and accuracy in working memory tasks: a meta-analytical comparison of effects. *Physiology & behavior,* 102**,** 421-428.

Mcmorris, T., Turner, A., Hale, B. J. & Sproule, J. 2016. Beyond the catecholamines hypothesis for an acute exercise-cognition interaction: a neurochemical perspective. *inExercise-Cognition Interaction: Neuroscience Perspectives, T. McMorris, Ed.*

Mcnair, D. M. 1971. *Manual profile of mood states*, Educational & Industrial testing service.

Mcnair, D. M., Droppleman, L. F. & Lorr, M. 1992. *Edits manual for the profile of mood states: POMS*, Edits.

Mead, L. A., Mayer, A. R., Bobholz, J. A., Woodley, S. J., Cunningham, J. M., Hammeke, T. A. & Rao, S. M. 2002. Neural basis of the Stroop interference task: response competition or selective attention? *Journal of the International Neuropsychological Society,* 8**,** 735-742.

Meeusen, R., Duclos, M., Foster, C., Fry, A., Gleeson, M., Nieman, D., Raglin, J., Rietjens, G., Steinacker, J. & Urhausen, A. 2013. Prevention, diagnosis and treatment of the overtraining syndrome: Joint consensus statement of the European College of Sport Science (ECSS) and the American College of Sports Medicine (ACSM). *European Journal of Sport Science,* 13**,** 1-24.

Meeusen, R., Watson, P., Hasegawa, H., Roelands, B. & Piacentini, M. F. 2007. Brain neurotransmitters in fatigue and overtraining. *Applied Physiology, Nutrition, and Metabolism,* 32**,** 857-864.

Mekari, S., Fraser, S., Bosquet, L., Bonnéry, C., Labelle, V., Pouliot, P., Lesage, F. & Bherer, L. 2015. The relationship between exercise intensity, cerebral oxygenation and cognitive performance in young adults. *European journal of applied physiology,* 115**,** 2189-2197.

Meyers, C. R., Zimmerli, W., Farr, S. D. & Baschnagel, N. A. 1969. Effect of strenuous physical activity upon reaction time. *Research Quarterly. American Association for Health, Physical Education and Recreation,* 40**,** 332-337.

Millet, G. P., Vleck, V. E. & Bentley, D. J. 2009. Physiological differences between cycling and running. *Sports Medicine,* 39**,** 179-206.

Millet, G. Y. & Lepers, R. 2004. Alterations of neuromuscular function after prolonged running, cycling and skiing exercises. *Sports medicine,* 34**,** 105-116.

Mitchell, R. L. & Phillips, L. H. 2007. The psychological, neurochemical and functional neuroanatomical mediators of the effects of positive and negative mood on executive functions. *Neuropsychologia,* 45**,** 617-629.

Mitrakou, A., Ryan, C., Veneman, T., Mokan, M., Jenssen, T., Kiss, I., Durrant, J., Cryer, P. & Gerich, J. 1991. Hierarchy of glycemic thresholds for counterregulatory hormone secretion, symptoms, and cerebral dysfunction. *American Journal of Physiology-Endocrinology And Metabolism,* 260**,** E67-E74.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A. & Wager, T. D. 2000. The unity and diversity of executive functions and their contributions to complex “frontal lobe” tasks: A latent variable analysis. *Cognitive psychology,* 41**,** 49-100.

Miyama, M. & Nosaka, K. 2004. Influence of surface on muscle damage and soreness induced by consecutive drop jumps. *The Journal of Strength & Conditioning Research,* 18**,** 206-211.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G. & Group, P. 2009. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *PLoS med,* 6**,** e1000097.

Moore, R. D., Romine, M. W., O'connor, P. J. & Tomporowski, P. D. 2012. The influence of exercise-induced fatigue on cognitive function. *Journal of sports sciences,* 30**,** 841-850.

Moreira, A., Bradley, P., Carling, C., Arruda, A. F. S., Spigolon, L. M., Franciscon, C. & Aoki, M. S. 2016. Effect of a congested match schedule on immune-endocrine responses, technical performance and session-RPE in elite youth soccer players. *Journal of sports sciences,* 34**,** 2255-2261.

Morgan, W., Brown, D., Raglin, J., O'connor, P. & Ellickson, K. 1987. Psychological monitoring of overtraining and staleness. *British journal of sports medicine,* 21**,** 107-114.

Motl, R., Berger, B. & Leuschen, P. 2000. The role of enjoyment in the exercise-mood relationship. *International Journal of Sport Psychology,* 31**,** 347-363.

Nakata, H., Yoshie, M., Miura, A. & Kudo, K. 2010. Characteristics of the athletes' brain: evidence from neurophysiology and neuroimaging. *Brain research reviews,* 62**,** 197-211.

Nederhof, E., Lemmink, K., Zwerver, J. & Mulder, T. 2007. The effect of high load training on psychomotor speed. *International journal of sports medicine,* 28**,** 595-601.

Nehlig, A. 2010. Is caffeine a cognitive enhancer? *Journal of Alzheimer's Disease,* 20**,** S85-S94.

Nemmi, F., Boccia, M., Piccardi, L., Galati, G. & Guariglia, C. 2013. Segregation of neural circuits involved in spatial learning in reaching and navigational space. *Neuropsychologia,* 51**,** 1561-1570.

Nibbeling, N., Oudejans, R. R., Ubink, E. M. & Daanen, H. A. 2014. The effects of anxiety and exercise-induced fatigue on shooting accuracy and cognitive performance in infantry soldiers. *Ergonomics,* 57**,** 1366-79.

Niendam, T. A., Laird, A. R., Ray, K. L., Dean, Y. M., Glahn, D. C. & Carter, C. S. 2012. Meta-analytic evidence for a superordinate cognitive control network subserving diverse executive functions. *Cognitive, Affective, & Behavioral Neuroscience,* 12**,** 241-268.

Nindl, B. C., Barnes, B. R., Alemany, J. A., Frykman, P. N., Shippee, R. L. & Friedl, K. E. 2007. Physiological consequences of US Army Ranger training. *Medicine and science in sports and exercise,* 39**,** 1380.

Nofuji, Y., Suwa, M., Moriyama, Y., Nakano, H., Ichimiya, A., Nishichi, R., Sasaki, H., Radak, Z. & Kumagai, S. 2008. Decreased serum brain-derived neurotrophic factor in trained men. *Neuroscience letters,* 437**,** 29-32.

Nougier, V., Ripoll, H. & Stein, J.-F. 1989. Orienting of attention with highly skilled athletes. *International Journal of Sport Psychology*.

Nougier, V., Stein, J.-F. & Bonnel, A.-M. 1991. Information processing in sport and" orienting of attention.". *International Journal of Sport Psychology*.

O'connor, P. J. 2006. Mental energy: Assessing the mood dimension. *Nutrition reviews,* 64**,** S7-S9.

Ogoh, S. & Ainslie, P. N. 2009. Cerebral blood flow during exercise: mechanisms of regulation. *Journal of applied physiology,* 107**,** 1370-1380.

Oweis, P. & Spinks, W. 2001. Biopsychological, affective and cognitive responses to acute physical activity. *Journal of sports medicine and physical fitness,* 41**,** 528.

Parfitt, G., Markland, D. & Holmes, C. 1994. Responses to physical exertion in active and inactive males and females. *Journal of Sport and Exercise Psychology,* 16**,** 178-186.

Parkinson, B., Totterdell, P., Briner, R. & Reynolds, S. 1996. *Changing moods: The psychology of mood and mood regulation*, Addison-Wesley Longman Limited.

Pauw, K. D., Roelands, B., Cheung, S. S., De Geus, B., Rietjens, G. & Meeusen, R. 2013. Guidelines to classify subject groups in sport-science research. *International journal of sports physiology and performance,* 8**,** 111-122.

Peluso, M. a. M. & Andrade, L. H. S. G. D. 2005. Physical activity and mental health: the association between exercise and mood. *Clinics,* 60**,** 61-70.

Penedo, F. J. & Dahn, J. R. 2005. Exercise and well-being: a review of mental and physical health benefits associated with physical activity. *Current opinion in psychiatry,* 18**,** 189-193.

Pescatello, L. S. 2014. *ACSM's guidelines for exercise testing and prescription 9th Ed.,* Philadelphia, Wolters Kluwer/Lippincott Williams & Wilkins Health.

Pesce, C. 2009a. An integrated approach to the effect of acute and chronic exercise on cognition: the linked role of individual and task constraints. *Exercise and cognitive function***,** 211-226.

Pesce, C. 2009b. An integrated approch to the effect of acute and chronic exercise on cognition: the linked role of individual and task constraints. *In:* MCMORRIS, T., TOMPOROWSKI, P. & AUDIFFREN, M. (eds.) *Exercise and cognitive function*

Oxford: John Wiley & Sons.

Pesce, C. & Audiffren, M. 2011. Does acute exercise switch off switch costs? A study with younger and older athletes. *J Sport Exerc Psychol,* 33**,** 609-26.

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**,** 275-292.

Pesce, C., Cereatti, L., Forte, R., Crova, C. & Casella, R. 2011. Acute and chronic exercise effects on attentional control in older road cyclists. *Gerontology,* 57**,** 121-8.

Pesce, C., Tessitore, A., Casella, R., Pirritano, M. & Capranica, L. 2007. Focusing of visual attention at rest and during physical exercise in soccer players. *Journal of Sports Sciences,* 25**,** 1259-1270.

Petruzzello, S. J., Landers, D. M., Hatfield, B. D., Kubitz, K. A. & Salazar, W. 1991. A meta-analysis on the anxiety-reducing effects of acute and chronic exercise. *Sports medicine,* 11**,** 143-182.

Piacentini, M. F., Witard, O. C., Tonoli, C., Jackman, S. R., Turner, J. E., Kies, A. K., Jeukendrup, A. E., Tipton, K. D. & Meeusen, R. 2016. Effect of Intensive Training on Mood With No Effect on Brain-Derived Neurotrophic Factor. *International journal of sports physiology and performance,* 11**,** 824-830.

Piepmeier, A. T. & Etnier, J. L. 2015. Brain-derived neurotrophic factor (BDNF) as a potential mechanism of the effects of acute exercise on cognitive performance. *Journal of Sport and Health Science,* 4**,** 14-23.

Plante, T. G., Gores, C., Brecht, C., Carrow, J., Imbs, A. & Willemsen, E. 2007. Does exercise environment enhance the psychological benefits of exercise for women? *International Journal of Stress Management,* 14**,** 88.

Polich, J. & Kok, A. 1995. Cognitive and biological determinants of P300: an integrative review. *Biological psychology,* 41**,** 103-146.

Pollock, M. L., Gaesser, G. A., Butcher, J. D., Després, J.-P., Dishman, R. K., Franklin, B. A. & Garber, C. E. 1998. ACSM position stand: the recommended quantity and quality of exercise for developing and maintaining cardiorespiratory and muscular fitness, and flexibility in healthy adults. *Med Sci Sports Exerc,* 30**,** 975-991.

Pontifex, M. B. & Hillman, C. H. 2007. Neuroelectric and behavioral indices of interference control during acute cycling. *Clinical Neurophysiology,* 118**,** 570-580.

Pontifex, M. B., Hillman, C. H., Fernhall, B., Thompson, K. M. & Valentini, T. A. 2009a. The effect of acute aerobic and resistance exercise on working memory. *Medicine & Science in Sports & Exercise,* 41**,** 927-934.

Pontifex, M. B., Hillman, C. H. & Polich, J. 2009b. Age, physical fitness, and attention: P3a and P3b. *Psychophysiology,* 46**,** 379-387.

Pronk, N. P., Crouse, S. F. & Rohack, J. J. 1995. Maximal exercise and acute mood response in women. *Physiology & behavior,* 57**,** 1-4.

Radel, R., Brisswalter, J. & Perrey, S. 2017. Saving mental effort to maintain physical effort: a shift of activity within the prefrontal cortex in anticipation of prolonged exercise. *Cognitive, Affective, & Behavioral Neuroscience,* 17**,** 305-314.

Raedeke, T. D. 2007. The relationship between enjoyment and affective responses to exercise. *Journal of Applied Sport Psychology,* 19**,** 105-115.

Raglin, J. S. & Morgan, W. P. 1985. Influence of vigorous exercise on mood state. *The Behavior Therapist*.

Rampinini, E., Impellizzeri, F. M., Castagna, C., Coutts, A. J. & Wisløff, U. 2009. Technical performance during soccer matches of the Italian Serie A league: Effect of fatigue and competitive level. *Journal of Science and Medicine in Sport,* 12**,** 227-233.

Rasmussen, P., Brassard, P., Adser, H., Pedersen, M. V., Leick, L., Hart, E., Secher, N. H., Pedersen, B. K. & Pilegaard, H. 2009. Evidence for a release of brain-derived neurotrophic factor from the brain during exercise. *Experimental physiology,* 94**,** 1062-1069.

Rattray, B., Argus, C., Martin, K., Northey, J. & Driller, M. 2015. Is it time to turn our attention toward central mechanisms for post-exertional recovery strategies and performance? *Frontiers in physiology,* 6**,** 79.

Reddy, S., Eckner, J. T. & Kutcher, J. S. 2014. Effect of Acute Exercise on Clinically Measured Reaction Time in Collegiate Athletes. *Medicine & Science in Sports & Exercise,* 46**,** 429-434.

Reed, J. & Ones, D. S. 2006. The effect of acute aerobic exercise on positive activated affect: A meta-analysis. *Psychology of Sport and Exercise,* 7**,** 477-514.

Reilly, T. & Edwards, B. 2007. Altered sleep–wake cycles and physical performance in athletes. *Physiology & behavior,* 90**,** 274-284.

Reilly, T. & Smith, D. 1986. Effect of work intensity on performance in a psychomotor task during exercise. *Ergonomics,* 29**,** 601-606.

Rietjens, G., Kuipers, H., Adam, J., Saris, W., Van Breda, E., Van Hamont, D. A. & Keizer, H. 2005. Physiological, biochemical and psychological markers of strenuous training-induced fatigue. *International journal of sports medicine,* 26**,** 16-26.

Rimmele, U., Seiler, R., Marti, B., Wirtz, P. H., Ehlert, U. & Heinrichs, M. 2009. The level of physical activity affects adrenal and cardiovascular reactivity to psychosocial stress. *Psychoneuroendocrinology,* 34**,** 190-198.

Roig, M., Nordbrandt, S., Geertsen, S. S. & Nielsen, J. B. 2013. The effects of cardiovascular exercise on human memory: a review with meta-analysis. *Neuroscience & Biobehavioral Reviews,* 37**,** 1645-1666.

Ronglan, L., Raastad, T. & Børgesen, A. 2006. Neuromuscular fatigue and recovery in elite female handball players. *Scandinavian journal of medicine & science in sports,* 16**,** 267-273.

Rose, E. A. & Parfitt, G. 2007. A quantitative analysis and qualitative explanation of the individual differences in affective responses to prescribed and self-selected exercise intensities. *Journal of Sport and Exercise Psychology,* 29**,** 281-309.

Roth, D. L. 1989. Acute emotional and psychophysiological effects of aerobic exercise. *Psychophysiology,* 26**,** 593-602.

Royal, K. A., Farrow, D., Mujika, I., Halson, S. L., Pyne, D. & Abernethy, B. 2006. The effects of fatigue on decision making and shooting skill performance in water polo players. *Journal of Sports Sciences,* 24**,** 807-815.

Russell, M. & Kingsley, M. 2011. Influence of exercise on skill proficiency in soccer. *Sports Medicine,* 41**,** 523-539.

Russell, M., Rees, G., Benton, D. & Kingsley, M. 2011. An exercise protocol that replicates soccer match-play. *International journal of sports medicine,* 32**,** 511-518.

Saanijoki, T., Nummenmaa, L., Eskelinen, J.-J., Savolainen, A. M., Vahlberg, T., Kalliokoski, K. K. & Hannukainen, J. C. 2015. Affective responses to repeated sessions of high-intensity interval training. *Med Sci Sports Exerc,* 47**,** 2604-11.

Saanijoki, T., Tuominen, L., Tuulari, J. J., Nummenmaa, L., Arponen, E., Kalliokoski, K. & Hirvonen, J. 2018. Opioid release after high-intensity interval training in healthy human subjects. *Neuropsychopharmacology,* 43**,** 246.

Saklofske, D., Blomme, G. & Kelly, I. 1992. The effects of exercise and relaxation on energetic and tense arousal. *Personality and Individual Differences*.

Salmela, J. H. J. H. 1986. Cognitive distortions during progressive exercise. *Perceptual and Motor Skills,* 63**,** 1067-1072.

Salmon, P. 2001. Effects of physical exercise on anxiety, depression, and sensitivity to stress: a unifying theory. *Clinical psychology review,* 21**,** 33-61.

Sanders, A. 1983. Towards a model of stress and human performance. *Acta psychologica,* 53**,** 61-97.

Saw, A. E., Main, L. C. & Gastin, P. B. 2015. Monitoring the athlete training response: subjective self-reported measures trump commonly used objective measures: a systematic review. *British journal of sports medicine***,** bjsports-2015-094758.

Schapschroer, M., Lemez, S., Baker, J. & Schorer, J. 2016. Physical Load Affects Perceptual-Cognitive Performance of Skilled Athletes: a Systematic Review. *Sports Med Open,* 2**,** 37.

Schapschröer, M., Lemez, S., Baker, J. & Schorer, J. 2016. Physical Load Affects Perceptual-Cognitive Performance of Skilled Athletes: a Systematic Review. *Sports Medicine-Open,* 2**,** 37.

Schlaffke, L., Lissek, S., Lenz, M., Brüne, M., Juckel, G., Hinrichs, T., Platen, P., Tegenthoff, M. & Schmidt-Wilcke, T. 2014. Sports and brain morphology–a voxel-based morphometry study with endurance athletes and martial artists. *Neuroscience,* 259**,** 35-42.

Schmit, C., Davranche, K., Easthope, C. S., Colson, S. S., Brisswalter, J. & Radel, R. 2015. Pushing to the limits: the dynamics of cognitive control during exhausting exercise. *Neuropsychologia,* 68**,** 71-81.

Schneider, S., Brümmer, V., Abel, T., Askew, C. D. & Strüder, H. K. 2009. Changes in brain cortical activity measured by EEG are related to individual exercise preferences. *Physiology & behavior,* 98**,** 447-452.

Schuhfried, G. 2009. Vienna Test System: computer-aided psychological diagnosis. *Mödling, Germany: Dr. G. Schuhfried Corporation*.

Scott, C. B., Littlefield, N. D., Chason, J. D., Bunker, M. P. & Asselin, E. M. 2006. Differences in oxygen uptake but equivalent energy expenditure between a brief bout of cycling and running. *Nutrition & metabolism,* 3**,** 1.

Scully, D., Kremer, J., Meade, M. M., Graham, R. & Dudgeon, K. 1998. Physical exercise and psychological well being: a critical review. *British journal of sports medicine,* 32**,** 111-120.

Secher, N. H., Seifert, T. & Van Lieshout, J. J. 2008. Cerebral blood flow and metabolism during exercise: implications for fatigue. *Journal of Applied Physiology,* 104**,** 306-314.

Shvartz, E. & Reibold, R. 1990. Aerobic fitness norms for males and females aged 6 to 75 years: a review. *Aviation, space, and environmental medicine,* 61**,** 3-11.

Sibley, B. A. 2006. Effects of an acute bout of exercise on cognitive aspects of stroop performance. *Journal of Sport and Exercise Psychology,* 28**,** 285-299.

Sinclair, W. & Artis, J. Passing ability of adolescent soccer players during 4-day tournament play. Science and Football VII: The Proceedings of the Seventh World Congress on Science and Football, 2013. Routledge, 273.

Sjöberg, H. 1975. Relations between heart rate, reaction speed, and subjective effort at different work loads on a bicycle ergometer. *Journal of Human Stress,* 1**,** 21-27.

Sjöberg, H. 1980. Physical fitness and mental performance during and after work. *Ergonomics,* 23**,** 977-985.

Skriver, K., Roig, M., Lundbye-Jensen, J., Pingel, J., Helge, J. W., Kiens, B. & Nielsen, J. B. 2014. Acute exercise improves motor memory: exploring potential biomarkers. *Neurobiology of learning and memory,* 116**,** 46-58.

Smith, M., Tallis, J., Miller, A., Clarke, N. D., Guimaraes-Ferreira, L. & Duncan, M. J. 2016a. The Effect of Exercise Intensity on Cognitive Performance During Short Duration Treadmill Running. *Journal of Human Kinetics,* 50**,** 27-35.

Smith, M. R., Coutts, A. J., Merlini, M., Deprez, D., Lenoir, M. & Marcora, S. M. 2016b. Mental fatigue impairs soccer-specific physical and technical performance. *Medicine & Science in Sports & Exercise,* 48**,** 267-276.

Smith, M. R., Marcora, S. M. & Coutts, A. J. 2015. Mental fatigue impairs intermittent running performance. *Med Sci Sports Exerc,* 47**,** 1682-90.

Soga, K., Shishido, T. & Nagatomi, R. 2015. Executive function during and after acute moderate aerobic exercise in adolescents. *Psychology of Sport and Exercise,* 16**,** 7-17.

Soligard, T., Schwellnus, M., Alonso, J.-M., Bahr, R., Clarsen, B., Dijkstra, H. P., Gabbett, T., Gleeson, M., Hägglund, M. & Hutchinson, M. R. 2016. How much is too much?(Part 1) International Olympic Committee consensus statement on load in sport and risk of injury. *Br J Sports Med,* 50**,** 1030-1041.

Solomon, R. L. & Corbit, J. D. 1974. An opponent-process theory of motivation: I. Temporal dynamics of affect. *Psychological review,* 81**,** 119.

Sparling, P., Giuffrida, A., Piomelli, D., Rosskopf, L. & Dietrich, A. 2003. Exercise activates the endocannabinoid system. *Neuroreport,* 14**,** 2209-2211.

Spies, K., Hesse, F. & Hummitzsch, C. 1996. Mood and capacity in Baddeley's model of human memory. *Zeitschrift für Psychologie mit Zeitschrift für angewandte Psychologie*.

Steinberg, H., Sykes, E. A., Moss, T., Lowery, S., Leboutillier, N. & Dewey, A. 1997. Exercise enhances creativity independently of mood. *British Journal of Sports Medicine,* 31**,** 240-245.

Steptoe, A. & Bolton, J. 1988. The short-term influence of high and low intensity physical exercise on mood. *Psychology and Health,* 2**,** 91-106.

Steptoe, A. & Cox, S. 1988. Acute effects of aerobic exercise on mood. *Health Psychology,* 7**,** 329.

Steptoe, A., Kearsley, N. & Walters, N. 1993. Acute mood responses to maximal and submaximal exercise in active and inactive men. *Psychology and Health,* 8**,** 89-99.

Stone, K. J. & Oliver, J. L. 2009. The effect of 45 minutes of soccer-specific exercise on the performance of soccer skills. *International Journal of Sports Physiology and Performance,* 4**,** 163-175.

Strauss, E., Sherman, E. M. & Spreen, O. 2006. *A compendium of neuropsychological tests: Administration, norms, and commentary*, American Chemical Society.

Strauss, P. S. & Carlock, J. 1966. Effects of load-carrying on psychomotor performance. *Percept Mot Skills,* 23**,** 315-20.

Streeter, C. C., Whitfield, T. H., Owen, L., Rein, T., Karri, S. K., Yakhkind, A., Perlmutter, R., Prescot, A., Renshaw, P. F. & Ciraulo, D. A. 2010. Effects of yoga versus walking on mood, anxiety, and brain GABA levels: a randomized controlled MRS study. *The Journal of Alternative and Complementary Medicine,* 16**,** 1145-1152.

Stroop, J. R. 1935. Studies of interference in serial verbal reactions. *Journal of experimental psychology,* 18**,** 643.

Stroth, S., Hille, K., Spitzer, M. & Reinhardt, R. 2009a. Aerobic endurance exercise benefits memory and affect in young adults. *Neuropsychological Rehabilitation,* 19**,** 223-243.

Stroth, S., Kubesch, S., Dieterle, K., Ruchsow, M., Heim, R. & Kiefer, M. 2009b. Physical fitness, but not acute exercise modulates event-related potential indices for executive control in healthy adolescents. *Brain research,* 1269**,** 114-124.

Suarez-Arrones, L. J., Nuñez, F. J., Portillo, J. & Mendez-Villanueva, A. 2012. Running demands and heart rate responses in men rugby sevens. *The Journal of Strength & Conditioning Research,* 26**,** 3155-3159.

Sudo, M., Komiyama, T., Aoyagi, R., Nagamatsu, T., Higaki, Y. & Ando, S. 2017. Executive function after exhaustive exercise. *European journal of applied physiology,* 117**,** 2029-2038.

Swann, C., Moran, A. & Piggott, D. 2015. Defining elite athletes: Issues in the study of expert performance in sport psychology. *Psychology of Sport and Exercise,* 16**,** 3-14.

Symonds, C., Gallagher, P., Thompson, J. & Young, A. 2004. Effects of the menstrual cycle on mood, neurocognitive and neuroendocrine function in healthy premenopausal women. *Psychological medicine,* 34**,** 93-102.

Tempest, G. D., Davranche, K., Brisswalter, J., Perrey, S. & Radel, R. 2017. The differential effects of prolonged exercise upon executive function and cerebral oxygenation. *Brain and cognition,* 113**,** 133-141.

Ten Haaf, T., Van Staveren, S., Iannetta, D., Roelands, B., Meeusen, R., Piacentini, M. F., Foster, C., Koenderman, L., Daanen, H. A. & De Koning, J. J. 2017. Changes in Choice Reaction Time During and After 8 Days Exhaustive Cycling are not Related to Changes in Physical Performance. *International journal of sports physiology and performance***,** 1-21.

Terry, P. 1995. The efficacy of mood state profiling with elite performers: A review and synthesis. *The Sport Psychologist,* 9**,** 309-324.

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**,** 141-153.

Themanson, J. & Hillman, C. 2006. Cardiorespiratory fitness and acute aerobic exercise effects on neuroelectric and behavioral measures of action monitoring. *Neuroscience,* 141**,** 757-767.

Thirlaway, K. & Benton, D. 1992. Participation in physical activity and cardiovascular fitness have different effects on mental health and mood. *Journal of psychosomatic research,* 36**,** 657-665.

Thomas, K., Goodall, S., Stone, M., Howatson, G., Gibson, A. S. C. & Ansley, L. 2015. Central and peripheral fatigue in male cyclists after 4-, 20-, and 40-km time trials. *Medicine & Science in Sports & Exercise,* 47**,** 537-546.

Thomas, R., Johnsen, L. K., Geertsen, S. S., Christiansen, L., Ritz, C., Roig, M. & Lundbye-Jensen, J. 2016. Acute Exercise and Motor Memory Consolidation: The Role of Exercise Intensity. *PLoS One,* 11**,** e0159589.

Thompson, K. G., Turner, L., Prichard, J., Dodd, F., Kennedy, D. O., Haskell, C., Blackwell, J. R. & Jones, A. M. 2014. Influence of dietary nitrate supplementation on physiological and cognitive responses to incremental cycle exercise. *Respiratory physiology & neurobiology,* 193**,** 11-20.

Thomson, K., Watt, A. & Liukkonen, J. 2009. Differences in ball sports athletes speed discrimination skills before and after exercise induced fatigue. *Journal of Sports Science and Medicine,* 8**,** 259-264.

Thorén, P., Floras, J. S., Hoffmann, P. & Seals, D. R. 1990. Endorphins and exercise: physiological mechanisms and clinical implications. *Medicine & science in sports & exercise*.

Toepper, M., Markowitsch, H. J., Gebhardt, H., Beblo, T., Thomas, C., Gallhofer, B., Driessen, M. & Sammer, G. 2010. Hippocampal involvement in working memory encoding of changing locations: an fMRI study. *Brain Research,* 1354**,** 91-99.

Tomlin, D. L. & Wenger, H. A. 2001. The relationship between aerobic fitness and recovery from high intensity intermittent exercise. *Sports Medicine,* 31**,** 1-11.

Tomporowski, P. D. 2003. Effects of acute bouts of exercise on cognition. *Acta psychologica,* 112**,** 297-324.

Tomporowski, P. D. 2005. Short-term effects of aerobic exercise on executive processes and emotional reactivity. *International Journal of Sport and Exercise Psychology,* 3**,** 131-146.

Tomporowski, P. D. & Ellis, N. R. 1986. Effects of exercise on cognitive processes: A review. *Psychological bulletin,* 99**,** 338.

Tomporowski, P. D., Ellis, N. R. & Stephens, R. 1987. The immediate effects of strenuous exercise on free-recall memory. *Ergonomics,* 30**,** 121-9.

Tomporowski, P. D., Mccullick, B., Pendleton, D. M. & Pesce, C. 2015. Exercise and children's cognition: the role of exercise characteristics and a place for metacognition. *Journal of Sport and Health Science,* 4**,** 47-55.

Tonoli, C., Heyman, E., Buyse, L., Roelands, B., Piacentini, M. F., Bailey, S., Pattyn, N., Berthoin, S. & Meeusen, R. 2014. Neurotrophins and cognitive functions in T1D compared with healthy controls: Effects of a high-intensity exercise. *Applied Physiology, Nutrition and Metabolism,* 40**,** 20-27.

Totterdell, P. 2000. Catching moods and hitting runs: Mood linkage and subjective performance in professional sport teams. *Journal of Applied Psychology,* 85**,** 848.

Travlos, A. K. & Marisi, D. Q. 1995. Information processing and concentration as a function of fitness level and exercise-induced activation to exhaustion. *Perceptual and Motor Skills*.

Tsai, C.-L., Chen, F.-C., Pan, C.-Y., Wang, C.-H., Huang, T.-H. & Chen, T.-C. 2014a. Impact of acute aerobic exercise and cardiorespiratory fitness on visuospatial attention performance and serum BDNF levels. *Psychoneuroendocrinology,* 41**,** 121-131.

Tsai, C.-L., Wang, C.-H., Pan, C.-Y., Chen, F.-C., Huang, T.-H. & Chou, F.-Y. 2014b. Executive function and endocrinological responses to acute resistance exercise. *Frontiers in behavioral neuroscience,* 8**,** 262.

Tseng, B. Y., Uh, J., Rossetti, H. C., Cullum, C. M., Diaz-Arrastia, R. F., Levine, B. D., Lu, H. & Zhang, R. 2013. Masters athletes exhibit larger regional brain volume and better cognitive performance than sedentary older adults. *Journal of Magnetic Resonance Imaging,* 38**,** 1169-1176.

Tsorbatzoudis, H., Barkoukis, V., Danis, A. & Grouios, G. 1998. Physical exertion in simple reaction time and continuous attention of sport participants. *Perceptual and Motor Skills,* 86**,** 571-576.

Tsukamoto, H., Suga, T., Takenaka, S., Tanaka, D., Takeuchi, T., Hamaoka, T., Isaka, T. & Hashimoto, T. 2016a. Greater impact of acute high-intensity interval exercise on post-exercise executive function compared to moderate-intensity continuous exercise. *Physiology & behavior,* 155**,** 224-230.

Tsukamoto, H., Suga, T., Takenaka, S., Tanaka, D., Takeuchi, T., Hamaoka, T., Isaka, T., Ogoh, S. & Hashimoto, T. 2016b. Repeated high-intensity interval exercise shortens the positive effect on executive function during post-exercise recovery in healthy young males. *Physiology & behavior,* 160**,** 26-34.

Vaile, J., Halson, S., Gill, N. & Dawson, B. 2008. Effect of hydrotherapy on recovery from fatigue. *International journal of sports medicine,* 29**,** 539-544.

Van Cutsem, J., Marcora, S., De Pauw, K., Bailey, S., Meeusen, R. & Roelands, B. 2017. The effects of mental fatigue on physical performance: a systematic review. *Sports Medicine***,** 1-20.

Van Den Heuvel, M. P. & Sporns, O. 2013. Network hubs in the human brain. *Trends in cognitive sciences,* 17**,** 683-696.

Van Dusen, D. P., Kelder, S. H., Kohl, H. W., Ranjit, N. & Perry, C. L. 2011. Associations of physical fitness and academic performance among schoolchildren. *Journal of School Health,* 81**,** 733-740.

Vandierendonck, A. 2014. Symbiosis of executive and selective attention in working memory. *Frontiers in human neuroscience,* 8**,** 588.

Vandierendonck, A., Kemps, E., Fastame, M. C. & Szmalec, A. 2004. Working memory components of the Corsi blocks task. *British journal of psychology,* 95**,** 57-79.

Veasey, R., Gonzalez, J., Kennedy, D., Haskell, C. & Stevenson, E. 2013. Breakfast consumption and exercise interact to affect cognitive performance and mood later in the day. A randomized controlled trial. *Appetite,* 68**,** 38-44.

Vestberg, T., Gustafson, R., Maurex, L., Ingvar, M. & Petrovic, P. 2012. Executive functions predict the success of top-soccer players. *PloS one,* 7**,** e34731.

Vissing, J., Andersen, M. & Diemer, N. H. 1996. Exercise-induced changes in local cerebral glucose utilization in the rat. *Journal of Cerebral Blood Flow & Metabolism,* 16**,** 729-736.

Voss, M. W. 2016. The chronic exercise-cognition interaction: fMRI research. *In:* MRCMORRIS, T. (ed.) *Exercise-Cognition Interaction: Neuroscience Perspectives.*

Voss, M. W., Erickson, K. I., Prakash, R. S., Chaddock, L., Malkowski, E., Alves, H., Kim, J. S., Morris, K. S., White, S. M. & Wójcicki, T. R. 2010. Functional connectivity: a source of variance in the association between cardiorespiratory fitness and cognition? *Neuropsychologia,* 48**,** 1394-1406.

Voss, M. W., Kramer, A. F., Basak, C., Prakash, R. S. & Roberts, B. 2009. Are expert athletes 'expert'in the cognitive laboratory? A meta-analytic review of cognition and sport expertise. *Applied Cognitive Psychology,* 24**,** 812-826.

Voss, M. W., Nagamatsu, L. S., Liu-Ambrose, T. & Kramer, A. F. 2011. Exercise, brain, and cognition across the life span. *Journal of applied physiology,* 111**,** 1505-1513.

Walsh, V. 2014. Is sport the brain's biggest challenge? *Current Biology,* 24**,** R859-R860.

Wang, C.-C., Chu, C.-H., Chu, I. H., Chan, K.-H. & Chang, Y.-K. 2013. Executive function during acute exercise: The role of exercise intensity. *Journal of Sport & Exercise Psychology,* 35**,** 358-367.

Wankel, L. M. 1993. The importance of enjoyment to adherence and psychological benefits from physical activity. *International Journal of Sport Psychology*.

Warburton, D. E., Nicol, C. W. & Bredin, S. S. 2006. Health benefits of physical activity: the evidence. *Canadian medical association journal,* 174**,** 801-809.

Weinstein, A. M., Voss, M. W., Prakash, R. S., Chaddock, L., Szabo, A., White, S. M., Wojcicki, T. R., Mailey, E., Mcauley, E. & Kramer, A. F. 2012. The association between aerobic fitness and executive function is mediated by prefrontal cortex volume. *Brain, behavior, and immunity,* 26**,** 811-819.

Whyte, E. F., Gibbons, N., Kerr, G. & Moran, K. A. 2015. Effect of a High-Intensity, Intermittent-Exercise Protocol on Neurocognitive Function in Healthy Adults: Implications for Return-to-Play Management After Sport-Related Concussion. *J Sport Rehabil,* Technical Notes 16**,** 2014-0201.

Wightman, E. L., Haskell-Ramsay, C. F., Reay, J. L., Williamson, G., Dew, T., Zhang, W. & Kennedy, D. O. 2015. The effects of chronic trans-resveratrol supplementation on aspects of cognitive function, mood, sleep, health and cerebral blood flow in healthy, young humans. *British Journal of Nutrition,* 114**,** 1427-1437.

Williams, S., Trewartha, G., Kemp, S. P., Brooks, J. H., Fuller, C. W., Taylor, A. E., Cross, M. J., Shaddick, G. & Stokes, K. A. 2017. How much rugby is too much? A seven-season prospective cohort study of match exposure and injury risk in professional rugby union players. *Sports medicine,* 47**,** 2395-2402.

Winter, B., Breitenstein, C., Mooren, F. C., Voelker, K., Fobker, M., Lechtermann, A., Krueger, K., Fromme, A., Korsukewitz, C., Floel, A. & Knecht, S. 2007. High impact running improves learning. *Neurobiol Learn Mem,* 87**,** 597-609.

Winter, E. M., Jones, A. M., Davison, R. R., Bromley, P. D. & Mercer, T. H. 2006. *Sport and Exercise Physiology Testing Guidelines: Volume I–Sport Testing: The British Association of Sport and Exercise Sciences Guide*, Routledge.

Woolery, A., Myers, H., Sternlieb, B. & Zeltzer, L. 2004. A yoga intervention for young adults with elevated symptoms of depression. *Alternative therapies in health and medicine,* 10**,** 60.

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**,** 1702-1710.

Yerkes, R. M. & Dodson, J. D. 1908. The relation of strength of stimulus to rapidity of habit-formation. *Journal of comparative neurology,* 18**,** 459-482.

Yeung, R. R. 1996. The acute effects of exercise on mood state. *Journal of psychosomatic research,* 40**,** 123-141.

Zervas, Y., Ekkekakis, P., Emmanuel, C., Psychoudaki, M. & Kakkos, V. The acute effects of increasing levels of aerobic exercise intensity on mood states. Proceedings of the 8th World Congress of Sport Psychology, 1993. 22-27.

Zoladz, J., Pilc, A., Majerczak, J., Grandys, M., Zapart-Bukowska, J. & Duda, K. 2008. Endurance training increases plasma brain-derived neurotrophic factor concentration in young healthy men. *J Physiol Pharmacol,* 59**,** 119-132.

Appendices

Appendix A: Example informed consent document

northumbria UNIVERSITY NEWCASTLE

INFORMED CONSENT FORM

Project title:

Participant ID:

Principal Investigator:

Investigator contact details:

	please tick or initial where applicable
I have carefully read and understood the Participant Information Sheet.	☐
I have had an opportunity to ask questions and discuss this study, and I have received satisfactory answers.	☐
I understand I am free to withdraw from the study at any time, without having to give a reason for withdrawing, and without prejudice.	☐
I agree to take part in this study.	☐
I would like to receive feedback on the overall results of the study at the email address given below. Email address……	☐

Signature of participant..... Date.....……..   (NAME IN BLOCK LETTERS).....…….
Signature of researcher..... Date.....……..   (NAME IN BLOCK LETTERS).....…….

INFORMED CONSENT FORM FOR REMOVAL AND STORAGE OF HUMAN TISSUE

Project title:

Participant ID:

Principal Investigator:

Investigator contact details:

I agree that the following tissue or other bodily material may be taken and used for the study:

Tissue/Bodily material	Purpose	Removal Method
Blood	For the assessment of lactate	via finger/ear lancet skin puncture

I understand that if the material is required for use in any other way than that explained to me, then my consent to this will be specifically sought. I understand that I will not receive specific feedback from any assessment conducted on my samples, but should any kind of abnormality be discovered then the investigator will contact me.

Method of disposal:

Clinical Waste ☒
Other ☐

If other please specify.....

Signature of participant..... Date.....……..

Signature of researcher..... Date.....……..

Appendix B: Example health questionnaire document

Date: ..... **Subject ID: .....**

Health Questionnaire

STRICTLY CONFIDENTIAL

Please answer these questions truthfully and completely. The purpose of this questionnaire is to ensure that you are fit and healthy to follow the proposed research programme.	**Please tick**	
	Yes	**No**

How would you describe your present level of activity? (please circle)		
Less than 1x per month	Once a month	
Once a week	Two/three times a week	
Four/five times a week	More than five times a week	
Do you feel faint or have spells of severe dizziness when undertaking exercise or otherwise?		
Have you had cause to suspend physical activity in the last two weeks for any reason?		
Are you suffering from any form of illness, injury, bone or joint problem, or have you done so in the last 4 weeks?		
Are you currently on any prescribed medication and/or have you taken any medication today?		
Do you have any allergies?		
Are you currently, or have you previously been a smoker?		
If you currently suffer from or have previously suffered from any of the following conditions, you will be unable to take part in the study. Please inform the researcher (without specifics) if as a result you will now be unable to take part in the study. • heart complaint/condition • asthma • diabetes (Type 1 or 2) • high blood pressure • blood borne disease or infection		
Is there any reason why you should not embark on the proposed research programme?		

You are not required to provide specifics of any condition that precludes you from taking part in the study. However, if you are not sure if any such condition will affect your ability to participate, please feel free to discuss this with the research team, although you are not obliged to do so.

Participant signature _____ Date _____

Authorised (signed by HPL Scientist) _____ Date _____

Appendix C: Example training history questionnaire

Date: ..... **Subject ID: .....**

Exercise History

STRICTLY CONFIDENTIAL

1. How often do you take part in high-intensity intermittent sport/exercise activity (e.g. training sessions, matches)?

   Less than 1x per month — Once a month

   Once a week — Two/three times a week

   Four/five times a week — More than five times a week

2. For how long have you taken part in the above exercise regimen?

   Less than 1 month — 1-3 months

   3-12 months — 12-24 months

   24 or more months

3. How would you consider your current level of fitness with regards to your own sport?

   Untrained — Moderately trained — Highly trained

4. How long have you been competitive in your sport (years)?

   …….

5. How many times, on average, do you train in your sport per week?

   …….

6. What is the duration, on average, of each training session (in minutes)?

   ……..

7. What is your estimated 16.1 km TT time (in minutes)? *Experimental studies 1 and 3 only*

   ……

8. What level of rugby do you currently play? *Experimental study 2 only*

   ……

9. Is there any reason why you feel you are not sufficiently trained to complete the protocol outlined in the Participant Information document?

Participant signature : _____ Date : _____

Sports scientist signature : _____ Date : _____

Appendix D: Bond-Lader mood scale (Bond and Lader, 1974)

"HOW DO YOU FEEL RIGHT NOW?"

Alert	_____	Drowsy
Calm	_____	Excited
Strong	_____	Feeble
Muzzy Headed	_____	Clear Headed
Well-Coordinated	_____	Clumsy
Lethargic	_____	Energetic
Contended	_____	Discontented
Troubled	_____	Tranquil
Mentally Slow	_____	Quick Witted
Tense	_____	Relaxed
Attentive	_____	Dreamy
Incompetent	_____	Proficient
Happy	_____	Sad
Antagonistic	_____	Friendly
Interested	_____	Board
Withdrawn	_____	Sociable

(Not to scale)

Appendix E: Mental and physical energy and fatigue scale (O`Connor 2006)

Directions. This part of the questionnaire asks about your current feelings of energy and fatigue. We are interested in how you feel right now, even if it is different than how you usually feel. Therefore, it is important that you focus on how you feel right now at this moment in responding to each item. There are no right or wrong answers. Please be as honest and accurate as possible in your responses. Make a vertical line through each horizontal line below to indicate the intensity of your current feelings. If you have a complete absence of the feeling described then place a vertical mark at the left edge of the horizontal line. If your feelings are the strongest intensity that you have ever experienced then place a vertical mark at the right edge of the horizontal line. If your feelings are between these two extremes, then use the distance from the left edge to represent the intensity of your feelings.

Example:

I feel I have no energy ——————————|—————————— Strongest feelings of energy ever felt

How do you feel right now with regard to your capacity to perform your typical ***PHYSICAL ACTIVITIES***....

29. I feel I have no energy ———————————————— Strongest feelings of energy ever felt
30. I feel no fatigue ———————————————— Strongest feelings of fatigue ever felt
31. I feel I have no vigor ———————————————— Strongest feelings of vigor ever felt
32. I feel no exhaustion ———————————————— Strongest feelings of exhaustion ever felt
33. I feel I have no pep ———————————————— Strongest feelings of pep ever felt
34. I have no feelings of being worn out ———————————————— Strongest feelings of being worn out ever felt

How do you feel right now with regard to your capacity to perform your typical ***MENTAL ACTIVITIES***....

29. I feel I have no energy ———————————————— Strongest feelings of energy ever felt
30. I feel no fatigue ———————————————— Strongest feelings of fatigue ever felt
31. I feel I have no vigor ———————————————— Strongest feelings of vigor ever felt
32. I feel no exhaustion ———————————————— Strongest feelings of exhaustion ever felt
33. I feel I have no pep ———————————————— Strongest feelings of pep ever felt
34. I have no feelings of being worn out ———————————————— Strongest feelings of being worn out ever felt

Appendix F: Example of online training log

Training Diary

Subject ID	PR 1009
Age	34
Date	15 July 2017
Week - Phase	Week 1 - 100% TL

TRAINING	Saturday	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday
Session One - Type	HIT	Endurance			Endurance	VO2max Test	Time Trial Test
Session One - Total Distance *(km)*	120	77			19		
Session One - Total Minutes	259	175	0	0	45	24	60
Session One - RPE	7	4			2	4	7
Zone 1 *(min)*	37	71			18	4	0
Zone 2 *(min)*	95	77			26	12	52
Zone 3 *(min)*	66	37			1	6	8
Zone 4 *(min)*	48	19			0	2	0
Zone 5 *(min)*	12	1			0	0	0

TRAINING	Saturday	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday
Session Two - Type						VO2max Test	
Session Two - Total Distance *(km)*							
Session Two - Total Minutes	0	0	0	0	0	9	0
Session Two - RPE						10	
Zone 1 *(min)*						0	
Zone 2 *(min)*						1	
Zone 3 *(min)*						2	
Zone 4 *(min)*						3	
Zone 5 *(min)*						3	

DAILY COMMENTS	
Saturday	Pretty punchy group ride , pretty much attacked every slight incline
Sunday	Easy Recovery Ride , legs felt pretty fried from Saturday so couldnt put any hard efforts in
Monday	Rest Day - really fatigued from the weekends riding
Tuesday	Working early and finishing late so couldnt get a session in
Wednesday	Easy 45 mins on Zwift (190W)
Thursday	
Friday	

Example of training load and heart rate data monitoring across an IT period, unseen by participants in a hidden excel tab.

Training Load & Heart Rate Data

Training Load	Week 1	Week 2	Week 3	Week 4	Week 5
Load	4406	7983	8630	1829	1803

Distance	Week 1	Week 2	Week 3	Week 4	Week 5
Distance	258	434	373	133	75